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SATURN V/VOYAGER LOAD RELIEF STUDY
FINAL REPORT

Prepared for

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Huntsville, Alabama

Contract NAS8-21171

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FOREWORD

This document comprises the Saturn V/Voyager load relief study final report prepared by Honeywell Inc. for the Astrodynamics Lab, George C. Marshall Space Flight Center, Huntsville, Alabama, under contract NAS8-21171.

The report documents the work performed on the second of two Saturn V/Voyager load relief studies. The results of the first study are contained in Reference 1 to this document. The purpose of both studies was the functional design of a load relief control system to increase the launch probability of the Saturn V launch vehicle with the Voyager payload.

Mr. John Livingston was the MSFC project director. Mr. John Larson was the project engineer at Honeywell. Mr. Lester Edinger acted as work director under Mr. Larson. The work was performed by Messrs. Thomas Hughes and James Lehfeldt.

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SECTION 1
INTRODUCTION

The objective of this study was the design of a load relief control system which would improve the launch probability of the Saturn V booster with the Voyager payload. The existing control system for the Saturn V S1-C stage was designed to meet the needs of the Apollo program; the Voyager payload, however, differs radically from the Apollo payload. For example, the Voyager payload has a long cylindrical section which would cause much higher bending moments at the instrument unit than would be experienced with the Apollo payload for a given angle of attack. The control system nevertheless is required to maintain structural loads within Saturn V/Apollo design limits. In addition to higher loads that will be experienced with the Voyager payload, the launch period is restricted to approximately a 45-day period every two years. The worst-launch period in terms of winds aloft under consideration was the October-November period in 1977. Marshall Space Flight Center (MSFC) concluded that because of these restrictions, either the Saturn V structure would have to be augmented or the existing Saturn V S1-C control system would have to be modified to enhance its load relief capability.

As a result, MSFC awarded Honeywell a study in June 1965 to define a control system for the Saturn V S1-C stage which would provide the necessary load relief for the Voyager payload configuration. This study was completed in January 1967 and is described in Reference 1 to this report. In fact, more load relief capability was provided than was required. However, it was also found that thrust misalignment could cause unacceptably large angles of attack at burnout. Because of time limitations this problem was not solved during the study, but alternative solutions were suggested. The two most promising solutions were: (1) to sacrifice some of the load relief capability, since the system had overachieved in load relief; and (2) and/or to add a drift rate feedback.

These factors, plus the fact that new ground rules were established, led NASA to award a second Saturn V/Voyager study in June 1967. This report describes the results of the second study. The new ground rules consisted primarily of new design constraints, revised terminal condition performance requirements, a revised payload configuration and a more severe launch period. The design constraints were imposed to reflect hardware mechanization considerations, such as how gains could be scheduled. The terminal condition performance requirements were modified by imposing a constraint on drift rate. The cylindrical section of the payload was reduced from a length of 54 feet to one of 45 feet. And finally, because of delays in the Voyager program, the last launch period was changed to the November-December period in 1979, which represents the worst-launch period in terms of winds aloft.

The system defined in the initial load relief study was designated the "LR-1" system. The objective of the second study was to modify this system as necessary to comply with the new ground rules. The system which resulted (referred to as the LR-2 system) did meet all the design constraints and performance requirements. In fact, although the requirement was only to provide sufficient load relief for the December wind magnitudes, acceptable load relief was provided for the larger annual wind magnitudes. Since the LR-2 system met the design constraints, its mechanization was relatively simple. A drift rate feedback was incorporated in this system to cope with the potential thrust misalignment problem. (MSFC has indicated that if fuel reserves for trajectory corrections are adequate, drift rates experienced without this drift rate feedback may be acceptable and the feedback eliminated.)

Use of a platform-mounted accelerometer for load relief, instead of the body-mounted accelerometer used in the LR-2 system, was briefly investigated at the end of the program. It was thought that use of the platform-mounted accelerometer would further reduce the complexity of the already simple LR-2 system. A system configuration was defined which met all performance requirements, with the exception of drift rate at burnout in the presence of thrust misalignment. There was insufficient time in the study, however, to finish the analysis of this system, but it was concluded that a satisfactory configuration could be defined.

Another interesting result of the study was the development of a synthesis procedure which proved to be an effective design tool in establishing control system compensation. The procedure establishes a frequency response requirement for the compensation on each of the feedbacks directly in terms of the given stability requirements. It is hoped that further development of the technique will lead to a useful procedure for handling trajectory constraints as well as stability constraints.

In Section 2 the recommended control system is described and its performance is summarized. In addition, conclusions and recommendations drawn from the study are listed. In Section 3, the problem is defined in terms of the vehicle model, the requirements, and the constraints. The Saturn/Apollo control system and the LR-1 system are described to provide background information for the present study. Then, in Section 4, development of the LR-2 system is described in detail, starting with the LR-1 system. Performance of the LR-2 system is also discussed in detail. Appendix A describes an analysis of the Saturn V/Apollo system modified to provide a load relief capability. In Appendix B, the load relief system which used the platform-mounted accelerometer is described. Frequency response plots and root locus plots are contained in Appendix C. Analog and digital computer trajectory runs are shown in Appendix D. The synthesis procedure used is discussed in Appendix E.

The basic vehicle data, equations of motion, data sources, performance requirements, design constraints, wind models, and pitch program are all contained in Reference 2. This reference was originally published in September 1967 and was revised in January 1968.

SECTION 2
SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

2.1 SUMMARY

The recommended load relief control system, designated the LR-2 configuration, was derived from the LR-1 load relief system described in Reference 1. Development of the LR-2 system consisted of defining intermediate system configurations, each of which was defined to meet a particular design constraint or performance requirement. Initial analyses were made to establish the deficiencies of the LR-1 system in terms of the new design constraints and performance requirements. Next, LR-1 system gain schedules were modified to provide the required trajectory performance in terms of allowed bending moment and terminal condition requirements. Revised gain schedules were defined using an analog computer time-varying flight simulation. This simulation proved to be very effective in determining the best tradeoff between bending moment and terminal condition performance. The resulting system was designated the "modified LR-1" system. Active filters in the modified LR-1 system were then replaced with passive filters, and all gains and compensation were placed on individual feedback paths. This system was termed the "preliminary LR-2" system. It met all performance requirements and design constraints except for the drift rate requirement at burnout in the presence of thrust misalignment. Also, stability margins, while acceptable, were not as large as desired. The final step in the development was to add a drift rate feedback to solve the drift rate problem and to modify system compensation and gain schedules to enhance stability margins. Stability margins were improved through use of a synthesis procedure defined during the study. In effect, the synthesis procedure established a frequency response requirement for the compensation on each feedback directly in terms of required stability margins.

The final system configuration, the "LR-2" system, is shown in Figure 1. It functions as an attitude control system during the first and last portions of the flight and as a load relief system during the time of high dynamic pressure in the middle of the flight. The system is designed to be used in both pitch and yaw axes during first-stage flight.

The LR-2 system has four feedbacks, consisting of attitude and attitude rate for attitude control, body normal acceleration for load relief, and drift rate to assure acceptable terminal condition performance. The attitude hold system used in the initial part of flight is switched to a load relief system by reducing attitude gain and increasing acceleration gain. Acceleration feedback, in effect, causes the vehicle to weathercock into the wind to reduce lateral loads. After the vehicle has passed through the region where large loads occur, the system is switched back to an attitude hold system. This type of operation not only results in maintaining loads within acceptable limits but also results in nearly drift-minimum performance at burnout, which is most desirable.

Figures 2, 3, and 4 show bending moment and drift rate performance obtained for yaw, head, and tail winds respectively. Only bending moment and terminal drift rate performance is shown since they proved to be the most taxing trajectory requirements to meet. Terminal drift and angle of attack were always well within the requirements. The load relief capability of the system was defined so that the worst-case bending moment (i. e., the Mach 1 yaw wind) would be just within the maximum allowable bending moment (5.4×10^5 Kg-m).

Figure 5 shows drift rate performance obtained in the presence of thrust misalignment with and without drift rate feedback for the worst-case winds. Without drift rate feedback, thrust misalignment caused drift rates on the order of 100 meters per second. With drift rate feedback added, the worst-case drift rate is shown to be about 73 meters per second. MSFC has indicated that the additional fuel needed to correct for the 100-meter-per-second

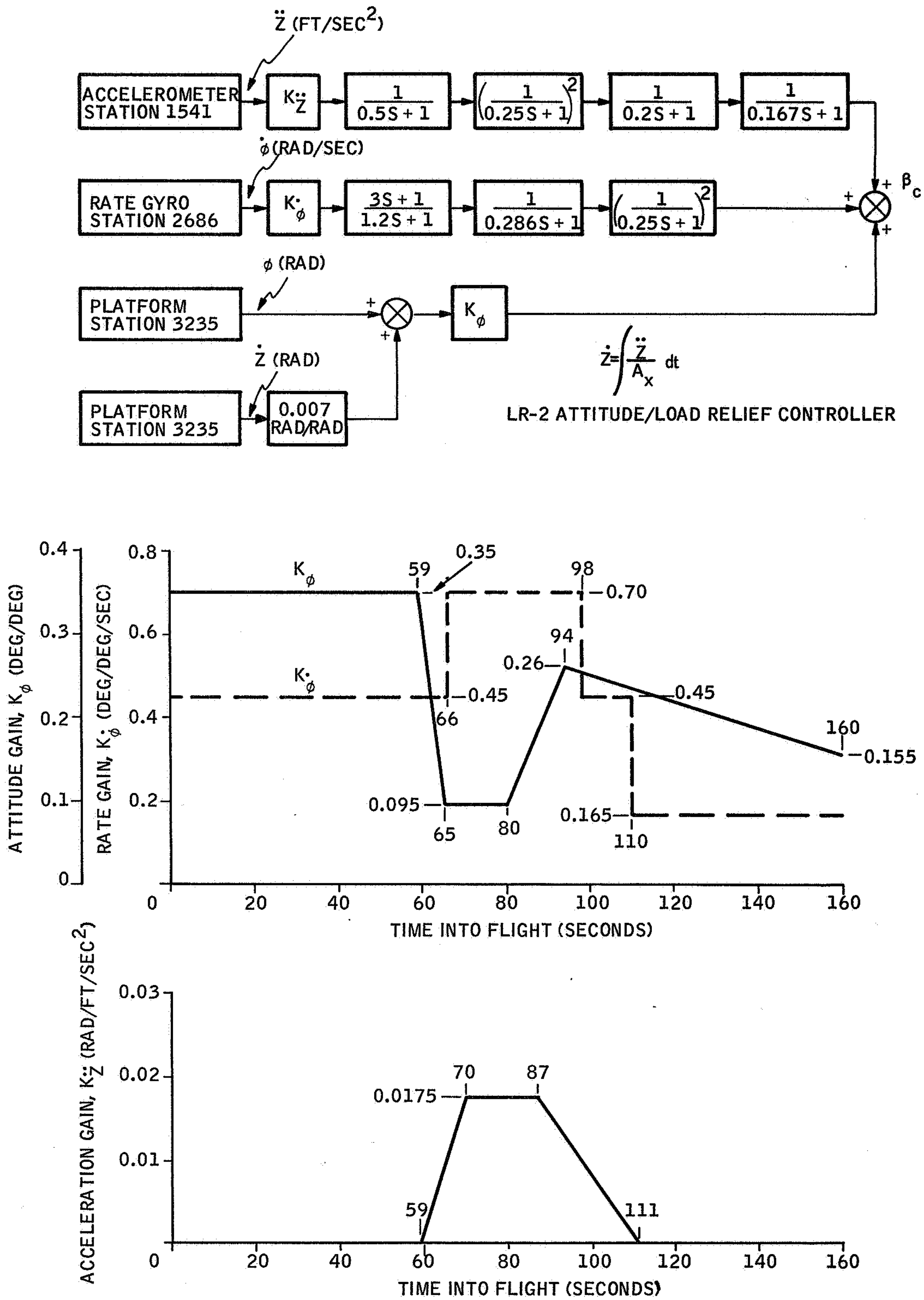


Figure 1. Recommended Load Relief Controller Block Diagram and Gain Schedules

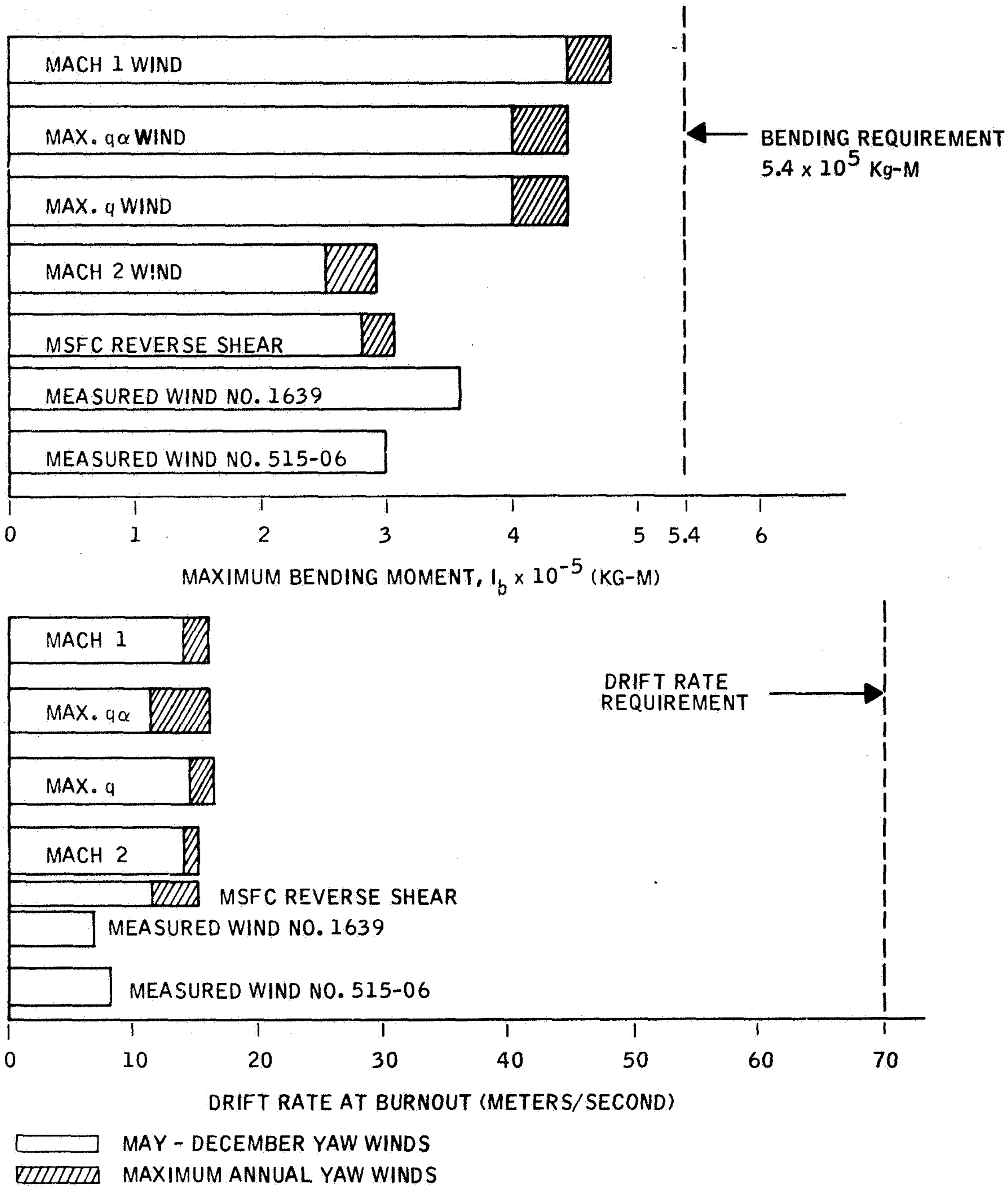


Figure 2. LR-2 Performance -- May-December Yaw Winds

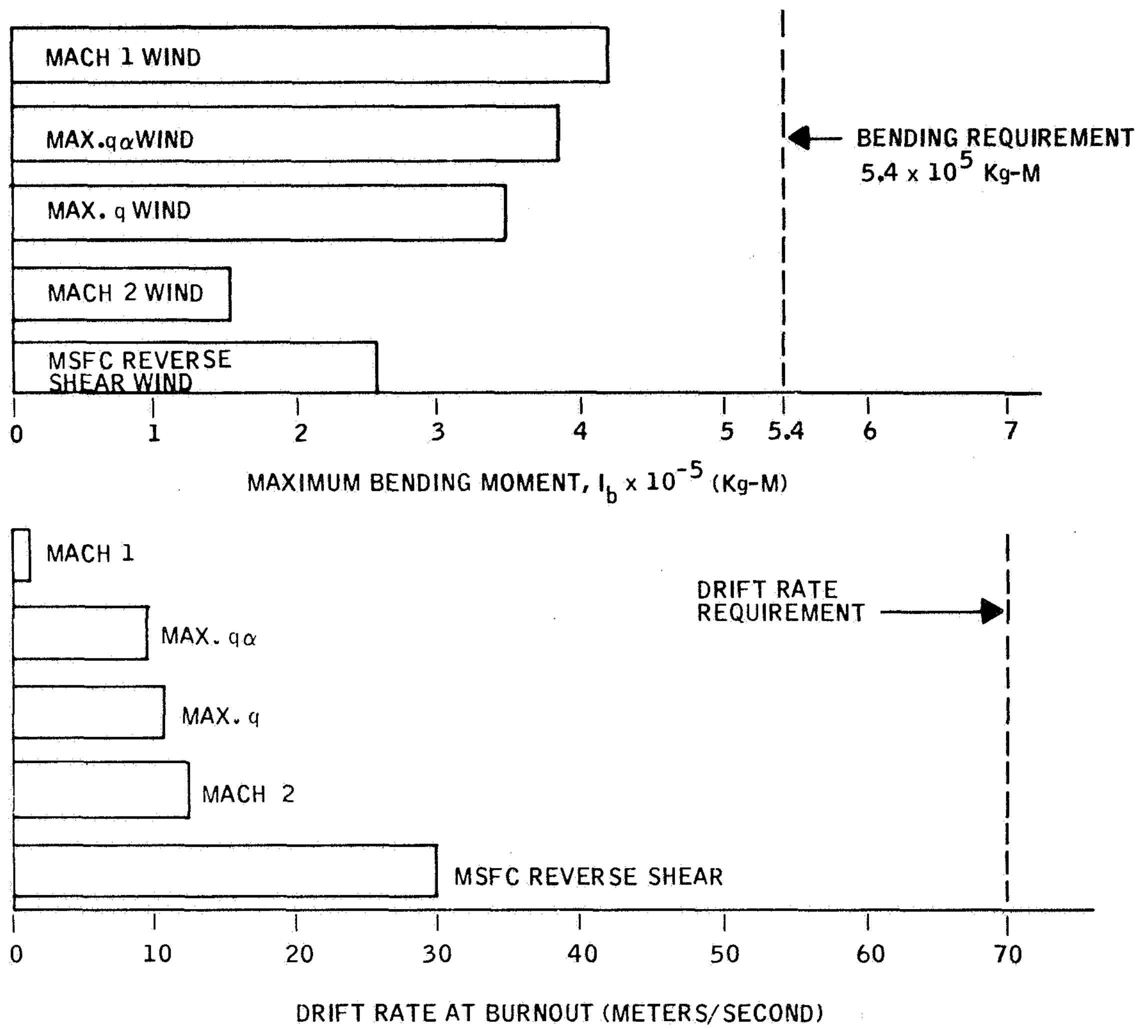


Figure 3. LR-2 Performance -- May-December Head Winds

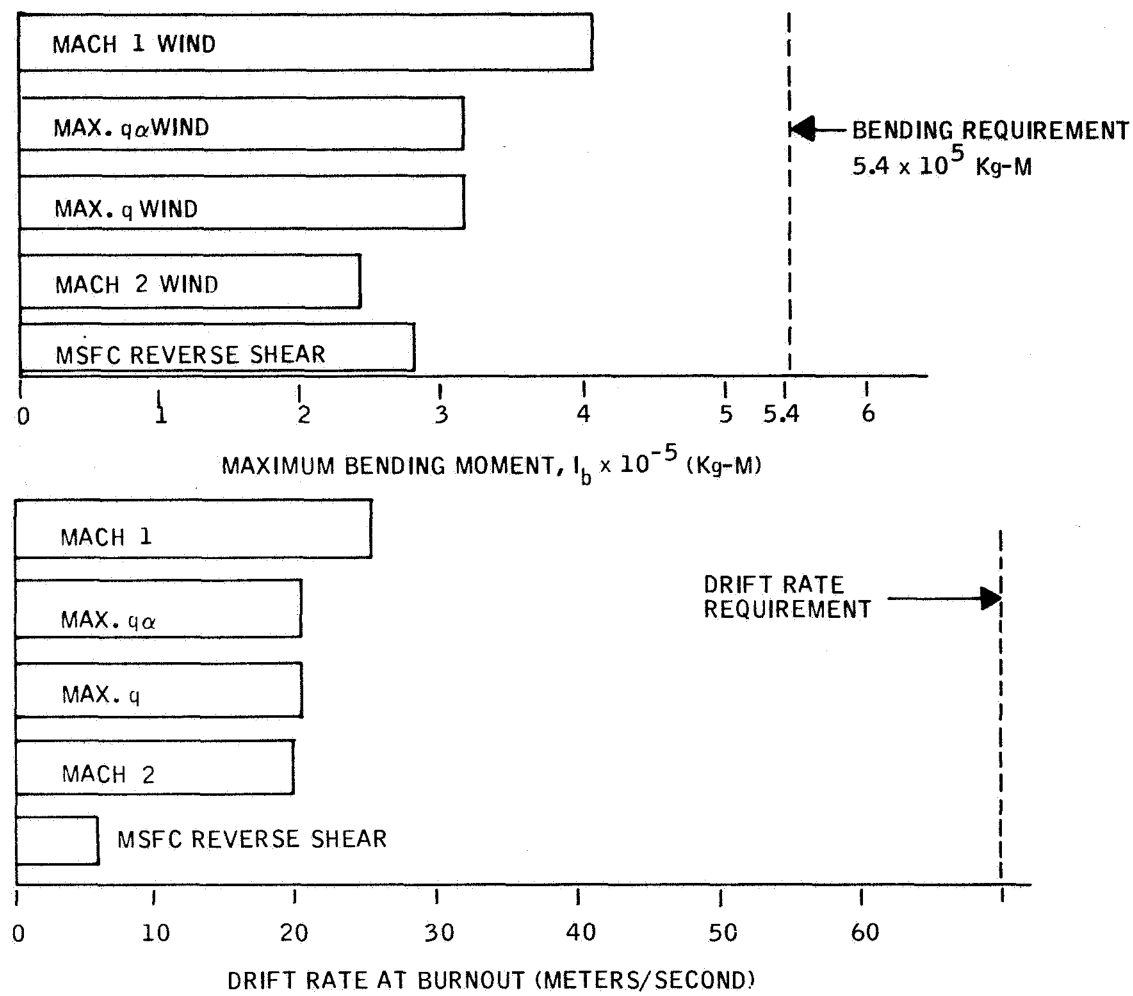


Figure 4. LR-2 Performance -- May-December Tail Winds

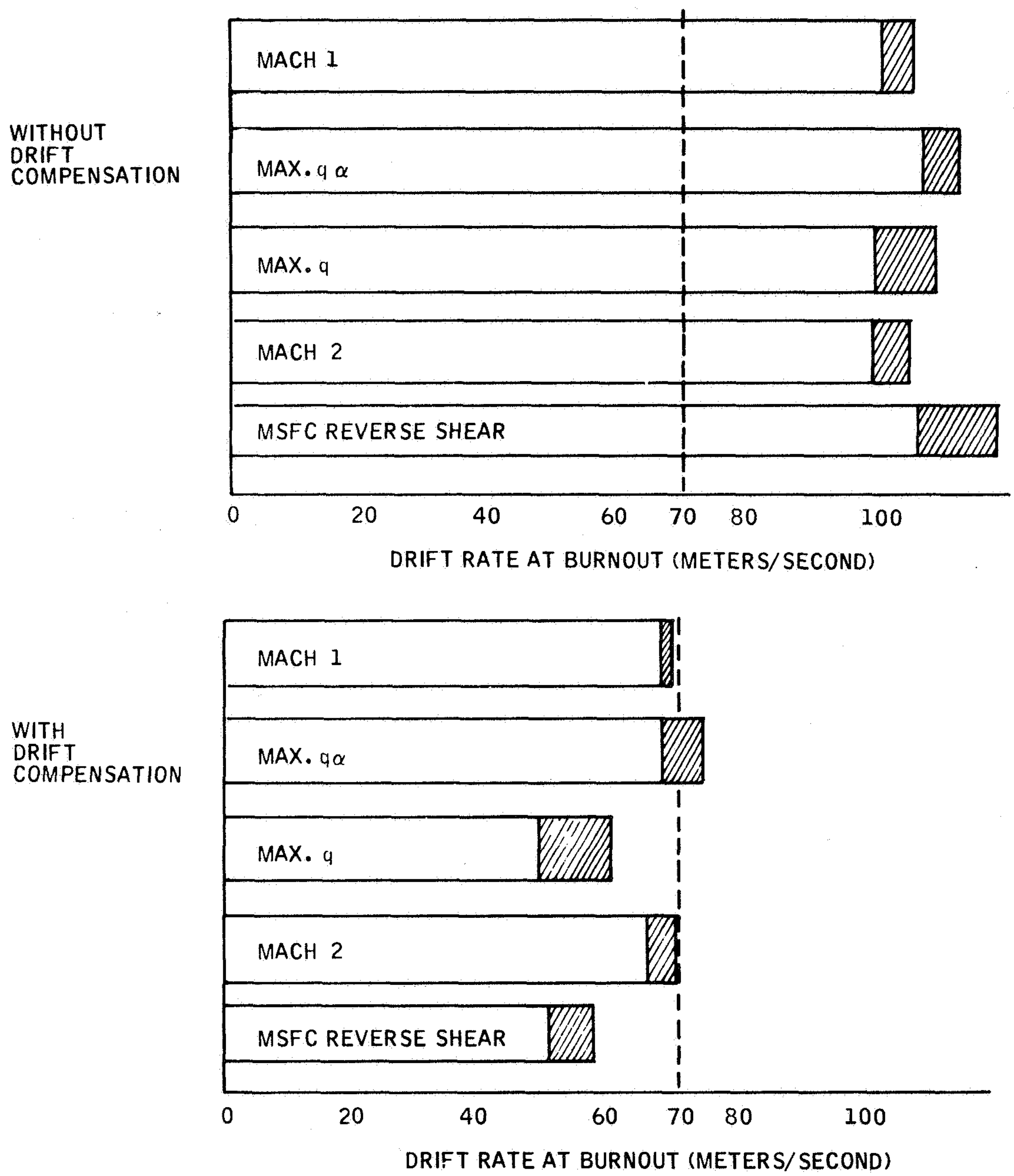


Figure 5. LR-2 Performance with +0.38-Degree Thrust Misalignment

drift rate is well within fuel reserves presently planned for the Voyager mission. However, MSFC has not established how much of these fuel reserves can be allocated to correct for trajectory errors caused by the control system. Should it be shown that fuel reserves are adequate, drift rate feedback can be eliminated without significantly affecting stability margins or load relief performance. This drift rate feedback is currently used on the upper stages and hence is a readily available signal from the platform. The actual signal used is the integral of the ratio of drift acceleration to longitudinal acceleration. This integrated signal is summed with the attitude error signal in the guidance computer. Consequently, its addition or elimination would represent no change in hardware mechanization but only a change in computer software. Summing the drift rate signal with the attitude error had the added advantage in that the drift rate signal is attenuated by the reduced attitude gain during the load relief portion of the flight. This minimizes its usual degrading effect upon the load relief function.

Table 1 lists stability margins obtained with the LR-2 system. As can be seen, all requirements have been met. The slosh modes and all but the first structural mode have been gain-stabilized by a least 6. 0 db. The first structural mode was phase-stabilized with a minimum phase margin of 103 degrees versus the minimum required 40-degree phase margin. System stability was maintained for all parameter variations considered. These parameter variations are described in detail in Section 3.

2.2 CONCLUSIONS

The conclusions are considered in two parts, those pertaining to LR-2 system design and those of a more general nature.

2.2.1 LR-2 System

1) The LR-2 system met all design constraints and performance requirements specified by MSFC. Although it was a requirement to meet

Table 1. Stability Margins -- Saturn V/Voyager, With LR-2 Control System

Time Into Flight (sec)	Lower Gain Margin (db)	Phase Margin (deg)	Upper Gain Margin (db)	Phase Margin First Bending Mode (1) (deg)
8.0	21.2	49.9	8.3	103.2
40.0	14.1	49.7	6.5	94.0 (2)
60.0	12.6	50.4	6.1	105.3 (2)
64.0	14.6	55.2	9.0	139.2 (2)
72.0	13.4	44.0	8.1	123.2 (2)
83.0	8.2	30.8	7.7	110.1 (2)
92.0	7.8	32.6	6.6	164.8
100.0	6.1	30.5	8.1	93.6 (2)
120.0	6.9	30.0	7.0	82.8 (2)
156.0	27.6	40.2	6.1	72.9 (2)
Required	6.0	30.0	6.0	40.0

(1) Second, third and fourth bending modes gain-stabilized.

(2) First bending mode gain-stabilized with less than 6 decibels gain margin. Phase margin determined at point where gain equals -6db.

the bending moment constraint for only the May-December wind magnitudes, this was accomplished for the larger annual wind magnitudes.

2) The objective of using only passive filtering was met, thus resulting in a relatively simple mechanization.

3) A drift rate feedback is required only to assure acceptable drift rates in the presence of thrust misalignment. Drift rates experienced without drift rate feedback in the presence of thrust misalignment may be acceptable, thus obviating the need for drift rate feedback. This will be determined by MSFC. Drift rate feedback can be removed without significantly affecting stability margins or load relief performance.

4) Without drift rate feedback, gain schedules used on other feedbacks in the system resulted in nearly drift-minimum trajectory performance at burnout. As a result, these gain schedules are considered nearly optimal in terms of minimizing trajectory errors due to such factors as thrust misalignment.

5) The analysis of a system which would use a platform-mounted accelerometer located at station 1541 resulted in a system which met all performance requirements except burnout drift rate in the presence of thrust misalignment. However, the apparent complexity of the system appeared to overshadow the potential savings gained in using the platform accelerometer. Unfortunately, only a short time was spent on system design. It was concluded that the system could have been greatly improved if more time had been available.

2.2.2 General

1) The vehicle model simplification made for the analog computer and digital computer trajectory studies resulted in a considerable economy in the study. Furthermore, the

validity of the simplifications was established by the excellent agreement shown by a comparison of trajectory results obtained using the simplified model and the complete model.

2) Analog and digital computer time-varying simulations proved to be effective design tools for establishing system parameters to meet trajectory constraints. Bending moment and terminal condition performance can be easily and rapidly evaluated to determine the best overall performance.

3) The synthesis technique developed during the study to define system compensation proved to be very effective. The technique in its present state of development is capable of defining the required system compensation directly in terms of stability requirements. It is anticipated the procedure could be extended to include the trajectory constraints to thus allow a complete system definition. In addition, it is concluded the synthesis procedure could be programmed on a digital computer to eliminate time consuming hand calculations.

2.3 RECOMMENDATIONS

2.3.1 LR-2 System

It is recommended that the use of a platform-mounted accelerometer be studied in more detail, as time did not permit a thorough analysis of this case during the program.

2.3.2 General

It is recommended that the synthesis procedure used in this study be developed further. It has the advantage of being able to establish system configuration requirements directly in terms of performance requirements and design constraints. Furthermore, it provides the designer with the insight into the problem needed to explain why a particular configuration is required.

SECTION 3
PROBLEM DEFINITION

3.1 INTRODUCTION

"Data Base Report for the Saturn V/Voyager Load Relief Study," (Reference 2), first published in September 1967 and updated in January 1968, documents all vehicle data used in this study. The Data Base summarizes performance requirements, design constraints, and system parameter variations to be considered during the design process, together with basic rigid and flexible vehicle data and aerodynamic data supplied by MSFC. In addition, the Data Base contains study equations required for controller synthesis and analysis, reduced coefficient data, and wind and trajectory profiles encountered during first-stage flight. The performance requirements, design constraints, and parameter variations defined in the Data Base Report are restated in this final report in Sections 3.2 through 3.4.

Complete equations describing the study model, presented in the Data Base, were simplified to facilitate vehicle simulations on the analog and digital computers. The validity of these simplified models is shown in Section 3.5.

Two Saturn V first-stage control systems developed prior to this study were evaluated in terms of constraints established for this current Voyager study. The LR-1 load relief system defined in a previous Saturn V/Voyager study was developed for the Saturn V/Voyager with the 54-foot cylindrical payload. The other system considered was the attitude control system used for the Saturn/Apollo mission. Both systems were found to be unacceptable for use on the current Saturn V/Voyager vehicle. These results are described in Section 3.6.

3.2 PERFORMANCE REQUIREMENTS

Performance requirements defined by NASA-MSFC and agreed to by Honeywell included first-stage terminal performance constraints, required stability margins, and allowable structural bending moments. These constraints provided guidelines for analysis and synthesis of load relief control for the Saturn V/Voyager with a 45-foot cylindrical payload.

The requirements shall be met when the vehicle is subjected to the following wind environments:

- Maximum MSFC 95 percent synthetic wind profile during mission launch period (May-December)
- MSFC measured wind profiles No. 1639 and No. 515-06.
- MSFC 99 percent reverse shear wind profile.

These wind profiles are presented in graphical form in Figures 5, 6, and 7 of Reference 2. Although the requirement is to provide acceptable performance for the May-December wind magnitudes for the 95 percent synthetic winds, it was an objective to provide acceptable performance for the larger annual wind magnitues.

3.2.1 Terminal Condition Performance Constraints

At first-stage burnout, the following performance shall be required:

- Maximum allowable angle of attack: 3.4 degrees
- Maximum allowable drift: 30,000 meters
- Maximum allowable drift rate: 70 meters per second

These constraints shall be met for all potential variations in vehicle/controller parameters, i. e., those listed in Section 3. 4. The above requirements, though agreed upon, are subject to revision by NASA pending the outcome of a study to define representative constraints corresponding to the payload requirements and planned fuel reserves for the Voyager mission.

3. 2. 2 Stability Margin Requirements

During first-stage flight, the following vehicle/controller stability margins shall be maintained:

- Upper gain margin at slosh and structural mode frequencies less than or equal to six decibels.
- Lower gain margin at rigid-body frequencies greater than or equal to six decibels.
- Phase margin at rigid-body and slosh mode frequencies greater than or equal to 30 degrees.
- Phase margin at first and second structural mode frequencies greater than or equal to 40 degrees.

System stability shall be maintained for all potential variations in vehicle/ controller parameters, i. e., those listed in Section 3. 4.

Stability margins were assumed to be defined in the classical sense. That is, gain margins are measured at the point at which phase angle equals ± 180 degrees. Phase margins are measured at the point at which system gain equals zero decibels.

3.2.3 Allowable Structural Bending Moment Requirement

Throughout first-stage flight, the total load experienced at any individual body station shall not exceed 80 percent of the ultimate load which would result in structural failure at that particular station. This requirement shall be met for all potential variations in vehicle and controller parameters, as listed in Section 3.4, when the vehicle is subjected to the most severe mission (May-December) wind profiles (described in Reference 2).

Allowable bending moment load limits at several vehicle stations as a function of time since launch are shown graphically in Figure 6. Data received from NASA-MSFC was reduced to this format to facilitate performance data reduction, since peak bending loads did not always occur at the time assumed (e.g., the maximum dynamic pressure or Mach 1 time points of the trajectory). Data at several stations is supplied, although station 3256, corresponding to the top of the instrument unit (IU), was found to be the most critical location on the vehicle axis.

3.3 SYSTEM DESIGN REQUIREMENTS

The constraints imposed by NASA-MSFC on the system design reflect the mechanization considerations established by the Saturn V/Apollo mission.

The following directives on system mechanization shall apply:

- Allowable sensors and sensor locations:
  - a) Attitude reference: Station 3235.
  - b) Rate gyro: Station 2686 is the present station (i.e., LR-1). Station 3235 could be used instead.
  - c) Linear accelerometer: Station 1541 is the present location (i.e., LR-1). Stations 2686 or 3235 may be used instead, if desired.

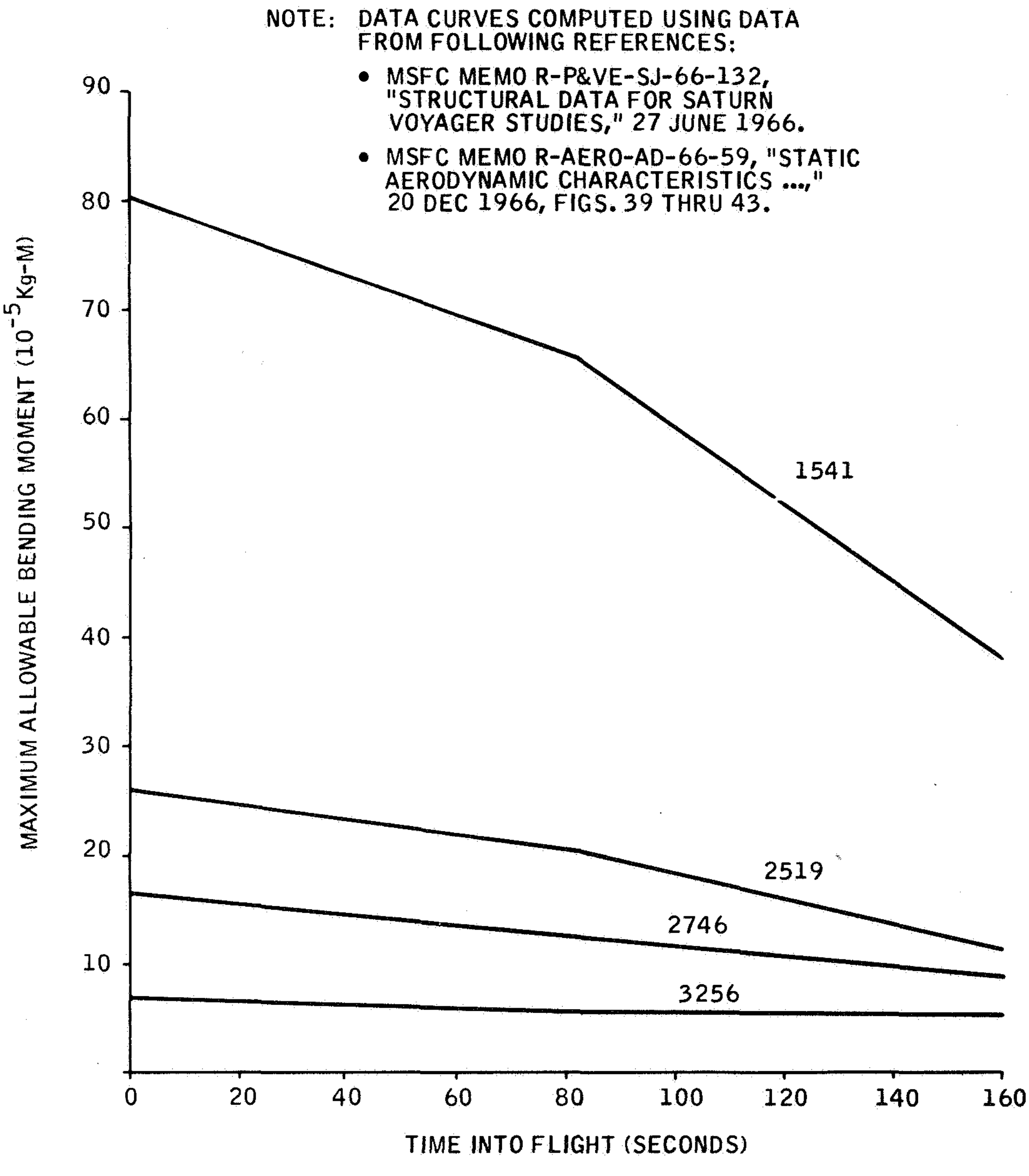


Figure 6. Bending-Moment Capability During First-Stage Flight

No other types of sensors will be allowed.

- Filtering shall be done only on individual feedbacks. No compensation on the summed signal to the gimbal actuator servo amplifier will be permitted.

- Passive filters shall be used if possible. Only if necessary to meet stability margin requirements will active filters be permitted. (A passive filter is defined as having real roots in the denominator of its transfer function. Active filters will have complex roots.)

- Gain scheduling shall be applied to individual feedback signals. No scheduling of error signal to servo amplifier will be allowed.

- Only two feedbacks (per channel) shall be continuously scheduled. Other scheduling must be accomplished in discrete steps.

3.4 PARAMETER VARIATIONS

The following vehicle/controller parameter variations will be considered when evaluating system performance and defining the functional block diagrams:

- Control system gains: ±10 percent

- Gain schedules: ±5 seconds

- Aerodynamic force coefficients ($C_{n\alpha}$): ± 10 percent

- Center of pressure minus center of gravity: ±127.8 inches error in the moment arm length

- Structural mode frequencies: ±20 percent
- Thrust: ±1.5 percent
- Engine gimbal offset: ±0.38 degree

These variations will be analyzed in a root-sum-squared (rss) manner to produce the largest deviation from nominal system performance.

3.5 EVALUATION OF MODEL SIMPLIFICATION

A simplified vehicle model was used in the digital and analog computer time-varying flight simulations. Use of a complete vehicle model was found to be unnecessary for these trajectory analyses. The validity of the simplified model used for the trajectory analyses is established in the following paragraphs.

Two factors motivated the development of a simplified vehicle model simulation:

1) A digital computer time-varying flight simulation using the complete vehicle model costs about $200 per trajectory to run. Hence, the use of the complete model simulation was too costly to use effectively as a design tool. Rather, its use was limited to performance verification.

2) An analog computer time-varying flight simulation using the complete model is cumbersome to set up and maintain.

As a result, the vehicle model was simplified for the design phase. A complete vehicle model time-varying digital simulation was used for final performance verification. The simplified vehicle model time-varying simulations (identical between the analog and digital computers) did not contain any slosh mode dynamics nor any third and fourth structural bending mode dynamics. In addition, aerodynamic coefficients in the first two bending mode equations were set to a constant value corresponding to the values occuring at the maximum dynamic pressure condition. The complete and simplified models are described in detail in Reference 2.

Both analog and digital simulations were used to cross check results. The analog computer simulation offered the advantage of economy, while the digital computer simulation had the advantage of accuracy.

Time history plots for the complete digital simulation and the simplified simulation are presented in Figure 7. The input wind is the May-December maximum $q\alpha$ tail wind. These time histories were obtained using the LR-2 load relief controller. They show that good agreement is obtained between the complete PARTNER digital simulation and the reduced PARTNER digital simulation. Small discrepancies are apparent in bending moment response in the 95-to-120-second time period. This is due to simplification of the first two bending modes and elimination of the third and fourth bending modes in the reduced simulation. In general, it is concluded from this comparison that use of the reduced vehicle model is valid for the trajectory analyses.

Time history plots comparing the reduced model digital simulation and the corresponding analog simulation are presented in Figure 8. These plots indicate that, in general, good agreement exists between the digital simulation and the analog simulation. Eight pot padders were used to generate time-varying coefficients used in analog simulation of the missile dynamics. Wind models

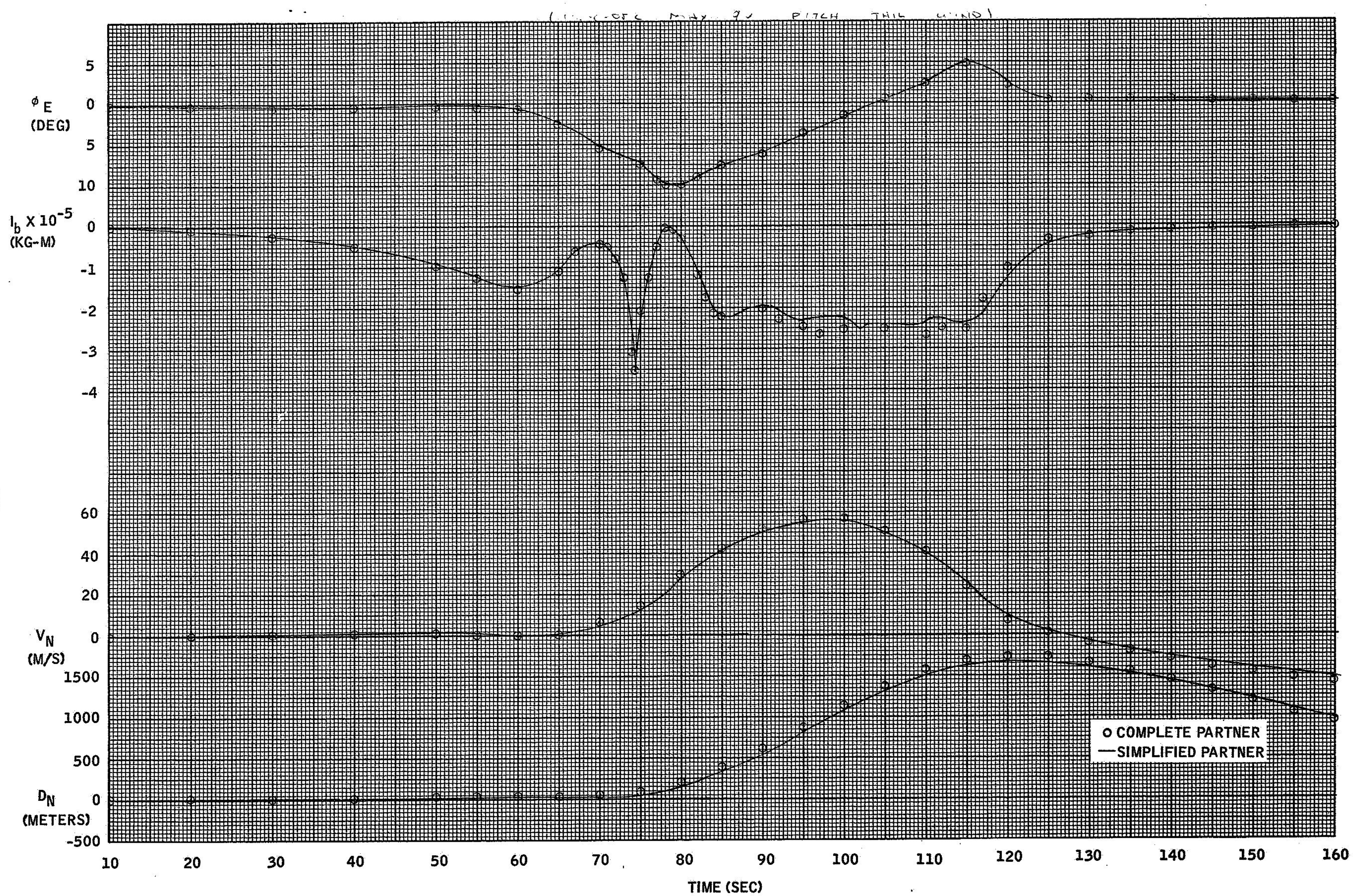


Figure 7. Comparison of Complete Model and Simplified Model Digital Simulation Results Obtained Using May-December Maximum $q\alpha$ Tailwind

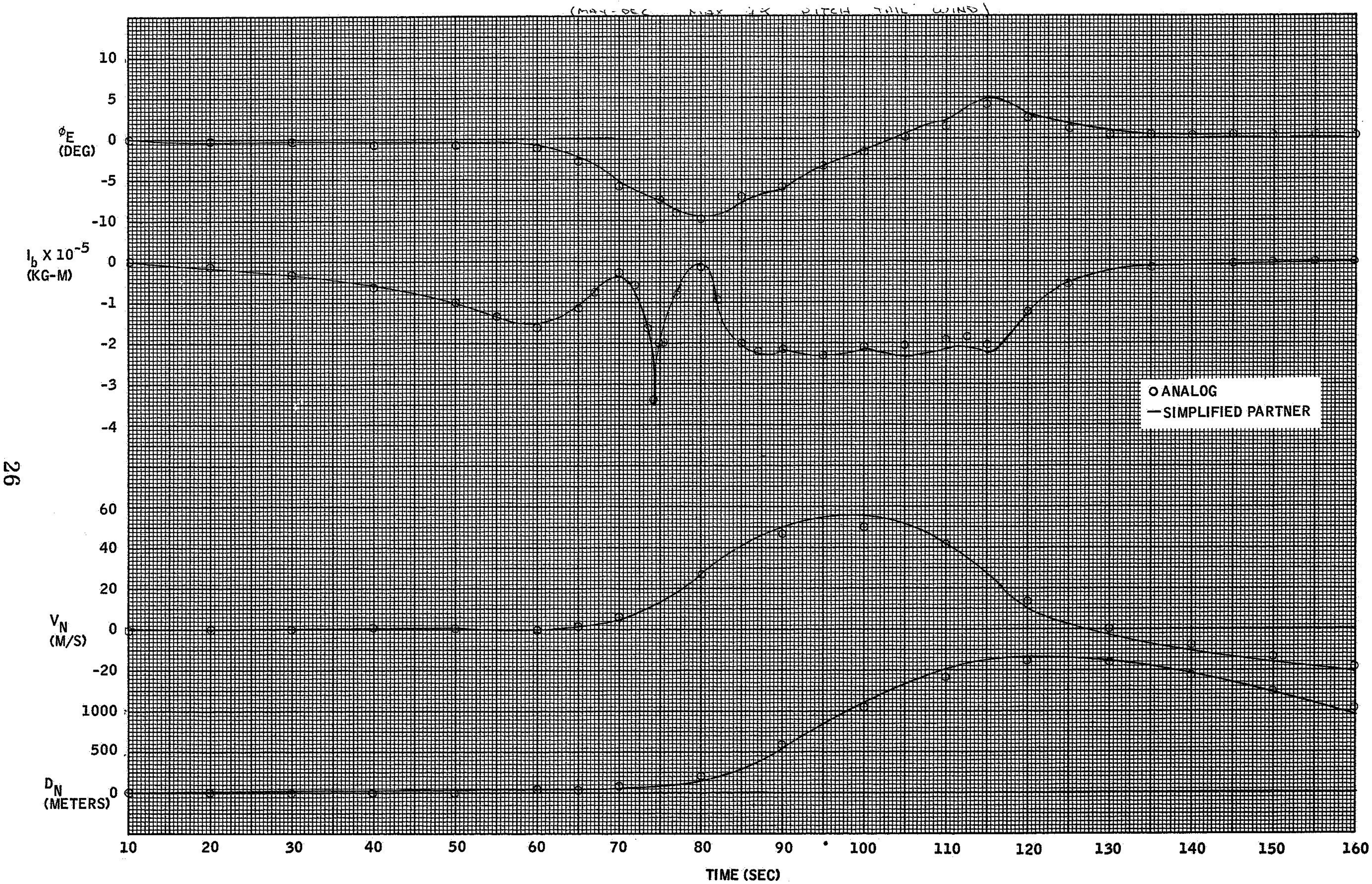


Figure 8. Comparison of Analog and Digital Computer Simplified Model Simulation Results Obtained Using May-December Maximum $q\alpha$ Tailwind

were simulated with diode function generators. The small discrepancies between the digital and analog simulation can be attributed to the time-varying function analog equipment.

3.6 DEFINITION OF CANDIDATE CONTROL SYSTEM

3.6.1 Background

As discussed in the previous Saturn V/Voyager study report (Reference 1), this vehicle, with pure attitude control, could experience bending moments in excess of the maximum allowable value at the instrument unit (station 3256). This is illustrated by performance data obtained for the Saturn V/Apollo SA-503 control system (see Figure 9). This data, listed in Table 2, was obtained with the short Voyager payload configuration (i.e., 45-foot cylindrical section). This data substantiated NASA-MSFC's conclusion that a load relief-type control system would be needed for the SaturnV/Voyager mission.

Table 2. Trajectory Performance Data[1] for Saturn V/ Apollo (SA-503) Control System - Saturn V/ Voyager (45-foot Payload)

Parameter	Performance	Requirement
Terminal Condition:		
Angle of attack (deg)	- 1.34	± 3.4
Drift displacement (km)	- 2.83	±30.0
Drift rate (m/s)	-31.5	±70.0
Bending Moment (10^5 kg-m):		
Station 1541	24.7	±55.0
Station 2519	13.2	±22.8
Station 2747	11.8	±14.5
Station 3256	7.2	± 5.4

(1) Data is for maximum $q\alpha$ yaw wind profile during May-December launch period.

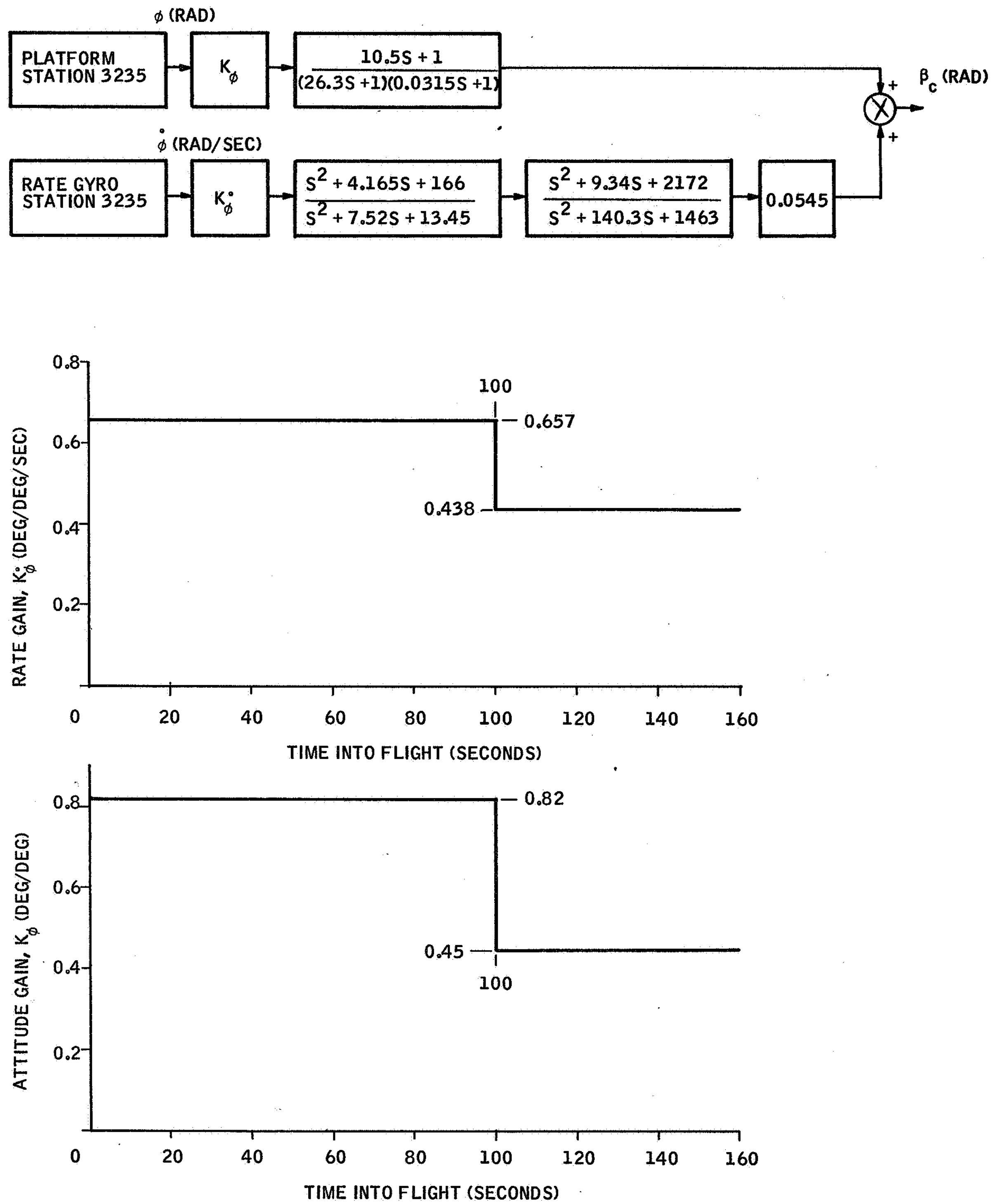


Figure 9. Saturn V/Apollo (SA 503) Attitude Controller Block Diagram and Gain Schedules

Since the pure attitude system functions to hold tight attitude, the lateral loads on the vehicle are reduced only because the vehicle builds up a drift rate in the downwind direction. But lateral loads could also be reduced by weathercocking the vehicle into the wind to build up an inertial angle of attack to cancel the wind angle of attack. The LR-1 system defined in the previous study does both. In the first part of flight the LR-1 system functions as an attitude hold system. Any loads due to a wind buildup during this portion of the flight will be partially reduced by a downwind drift of the vehicle. In the middle of the flight, the system is switched to an acceleration feedback system. This causes the vehicle to weathercock, resulting in further load reduction. After the vehicle has passed through the region of high dynamic pressure, the system is switched back to an attitude control function to check the upwind drift. This is done to assure acceptable terminal condition performance.

Because of these desirable features of the LR-1 system, the design philosophy in this study was to consider the LR-1 system as the sole candidate control system for the study. The study approach was to define the changes in the LR-1 system configuration required to meet the NASA-MSFC-imposed design constraints and performance requirements.

3.6.2 Problem Area Definition

Figure 10 is a block diagram of the LR-1 attitude/load relief control system defined in the previous Saturn V/Voyager load relief study. Performance of this system on the longer payload Voyager configuration was considered unsatisfactory in terms of meeting all performance requirements. This is best illustrated by data extracted from the earlier study final report and presented in Table 3. The system overachieved in terms of bending moment reduction but exceeded the allowable angle of attack at burnout.

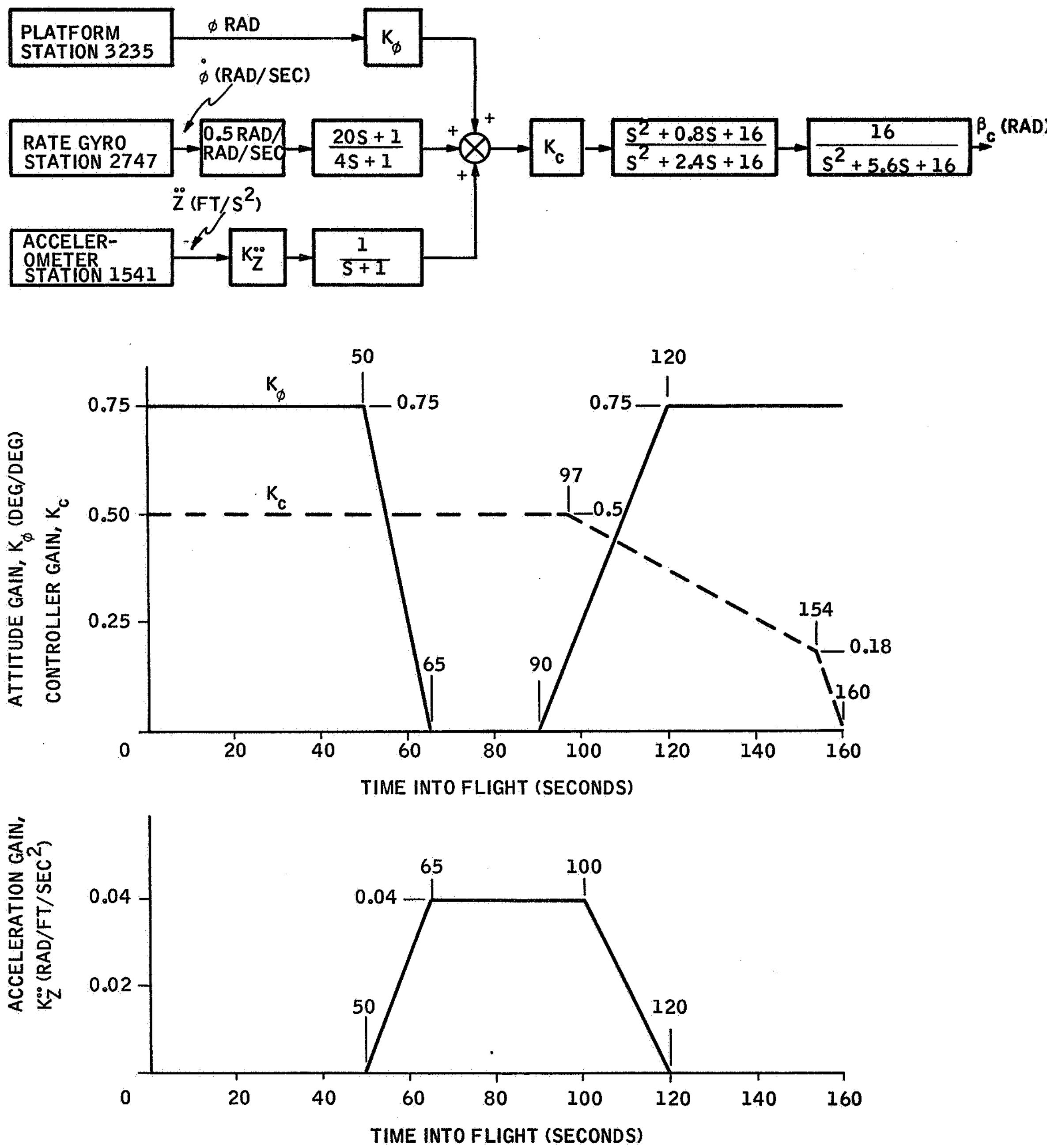


Figure 10. Saturn V/Voyager (82-foot payload) LR-1 Attitude/Load Relief Controller Block Diagram and Gain Schedules

Table 3. Trajectory Performance Data for LR-1 Control System on Saturn V/Voyager (54-Foot Payload)

Parameter	Performance			Requirement
	Max $q\alpha$ Wind[1]	1639 Wind[2]	515-06 Wind[3]	
Terminal Condition:				
Angle of attack (deg)	4.96	5.95	4.58	± 3.4
Drift displacement (km)	- 9.18	- 15.45	- 16.20	±35.0
Drift rate (m/s)	-115.3	-189.5	-141.2	None
Bending Moment (10^5 kg-m):				
Station 1541	9.54	13.07	10.15	±57.1
Station 2519	6.07	8.29	6.45	±17.4
Station 2746	5.28	7.22	5.61	±11.2
Station 3256	3.14	4.32	3.32	± 5.4

(1) Maximum $q\alpha$ synthetic yaw wind profile during May-November launch period.

(2) Measured wind profile. Maximum peak yaw wind speed 79.02 meters per second at maximum q.

(3) Measured wind profile. Maximum shear rate to peak yaw wind speed of 60.61 meters per second.

It is of interest at this point to compare the LR-1 load reduction performance (Table 3) with that obtained with the Saturn V/Apollo system (Table 2). This comparison shows the bending moments experienced with the LR-1 system were smaller by at least a factor of two, not only at the instrument unit but along the entire length of the vehicle.

Because of reduced vehicle length (45-foot payload), increased mission wind magnitudes (May-December launch period), and a more complete vehicle data package, performance of the LR-1 system on the Saturn V/Voyager was redefined to determine the candidate's load reduction capability and the vehicle's boost cutoff trajectory conditions. The performance data obtained is presented in Table 4. A direct comparison of this data with data for the longer Voyager (Table 3) showed the load relief capability of LR-1 to be undiminished. Bending moment at station 3256 remained 3.15×10^5 kg-m, well within the allowable 5.4×10^5 kg-m. The reduction in vehicle length relaxed structural loads due to angle of attack as expected, but the increased mission winds resulted in net peak loads which matched those of the previous Voyager study.

In contrast to load relief performance, terminal condition performance of the vehicle with LR-1 deteriorated when the configuration was shortened and the wind model modified. Drift rate and angle of attack, for example, were increased from 115.3 meters per second and 4.96 degrees (Table 3) to 180 meters per second and 5.5 degrees (Table 4) for the maximum $q\alpha$ yaw wind model. This performance, excessive according to specification, does not include the effects of three-sigma uncertainties in vehicle and control system parameters. If thrust misalignment were accounted for, these conditions would become roughly double the quoted value as illustrated by results given in Reference 1 and by data of Section 4, this report. To improve performance

Table 4. Trajectory Performance Data for LR-1 Control System on Saturn V/Voyager (45-Foot Payload)

Parameter	Performance			Requirement
	Yaw Wind (1)	Tail Wind (1)	Head Wind (1)	
Terminal Condition:				
Angle of attack (deg)	5.5	- 4.5	1.6	± 3.4
Drift displacement (km)	- 13.3	12.4	- 4.1	±30.0
Drift rate (m/s)	-180.0	202.0	-52.0	±70.0
Bending Moment (10^5 kg-m):				
Station 3256	3.15	- 3.25	2.6	± 5.4

(1) Maximum $q\alpha$ synthetic wind profile during May-December launch period.

at first-stage burnout by the necessary amount, the load reduction capability of the LR-1 must be sacrificed. This conclusion is in agreement with the recommendation made in Reference 1.

Stability margins for the Saturn V/Voyager short-payload configuration with the LR-1 control system are listed in Table 5. This data shows that although acceptable stability is achieved at these conditions, stability margins are marginal. This is evidenced primarily at conditions after maximum q and less than 110 seconds into the flight.

3.6.3 Recommended Modifications

Based on the trajectory and stability results described above for the LR-1 system, it was concluded that terminal condition performance and stability margins could be improved by reducing the load relief capability. The LR-1 system configuration, when reviewed with regard to the new design constraints (Section 3.3), was found to require the following modifications if it was to be recommended for use with the short-payload-length Saturn V/Voyager vehicle configuration:

- A change from active to passive compensation
- Placement of all compensation and gain scheduling on the feedback paths.
- Scheduling of two rather than three variable gains. The third is to be varied in discrete steps.
- Relocation of rate gyro from station 2747 to 2686. Station 2686 was chosen because it was closest of the allowable stations to station 2747.

Table 5. Stability Margins for LR-1 Control System on Saturn V/Voyager (45-Foot Payload)

Time Into Flight (sec)	Lower Gain Margin (db)	Phase Margin (deg)	Upper Gain Margin (db)	Phase Margin, First Mode (1) (deg)
8	20.8	54.0	6.6	49.1
40	13.5	53.1	4.8	60.7
60	13.6	60.9	5.2	99.7
64	18.0	63.6	5.8	92.1
72	13.2	50.4	6.5	102.8
83	6.6	24.3	6.9	99.6
92	5.8	21.8	8.1	92.1
100	7.1	26.1	8.9	87.6
120	8.5	48.0	7.7	70.0
156	23.4	58.4	8.7	85.0

(1) Second, third, and fourth structural modes are gain-stabilized.

SECTION 4
EVOLUTION OF RECOMMENDED LOAD RELIEF CONTROL SYSTEM

4.1 INTRODUCTION

This section describes the evolution of the final recommended LR-2 load relief control system, starting from control system LR-1 defined during the previous Saturn V/Voyager study conducted by Honeywell under NASA-MSFC contract NAS 8-11206.

A sequence of three control system configurations were defined during the study, starting with the LR-1 system. Each control system configuration represents a significant step toward elimination of the deficiencies in the LR-1 control system with respect to the performance criteria and design contraints imposed for this second Saturn V/Voyager study. The first step in the configuration development was to improve trajectory performance of the LR-1 system. This was accomplished by modifying existing gain schedules. Drift rate performance at burnout was improved at the expense of load relief capability. Bending moment response was also made less sensitive to the effects of thrust misalignment. This system was called the "modified LR-1" System. The modified LR-1 system exhibited acceptable trajectory performance but did not meet the design constraints imposed for the second study. In addition to defining the modified LR-1 system, a brief analysis of the Saturn/Apollo control system was made to determine if the current Apollo system could be simply modified to provide acceptable Voyager load relief. Incomplete performance results, presented in Appendix A, indicated that a satisfactory load reduction capability could be obtained but that terminal performance of the system would be degraded.

The "preliminary LR-2" load relief control system represents the second step in the configuration development. In this system the active filters in the modified LR-1 System were replaced with passive networks. These passive networks were then moved to the individual feedback paths. The preliminary LR-2 System met the performance requirements and design constraints for the nominal vehicle configuration. Stability margins however, were marginal at some time points. In addition, inclusion of thrust misalignment resulted in drift rates at burnout larger than the allowed value.

The LR-2 System represents the third and final step in the configuration development. A synthesis technique was developed and applied to the preliminary LR-2 configuration to improve stability and phase margins. The stability analysis resulted in improved gain and phase margins. The Drift rate performance at burnout, with thrust misalignment, was made acceptable with the addition of a drift rate feedback.

4.2 ANALYSIS OF MODIFIED LR-1

The modified LR-1 system block diagram and gain schedules are shown in Figure 11. The modified LR-1 system consists of an LR-1 system with revised gain schedules. The attitude and acceleration gain schedules were modified to improve drift rate performance at some expense in bending moment reduction. This tradeoff was possible because the LR-1 system had more load relief capability than was required. In general, the attitude and acceleration gain schedules were compressed in time. This reduced the period of time that the control system functioned as a load relief control system. A direct result of this modification is a large reduction in the upwind drift rate at burnout. It should also be noted that the attitude gain schedule is not reduced to zero during the period of load relief. This reduces the weathercocking and ultimately reduces drift rate and drift at burnout.

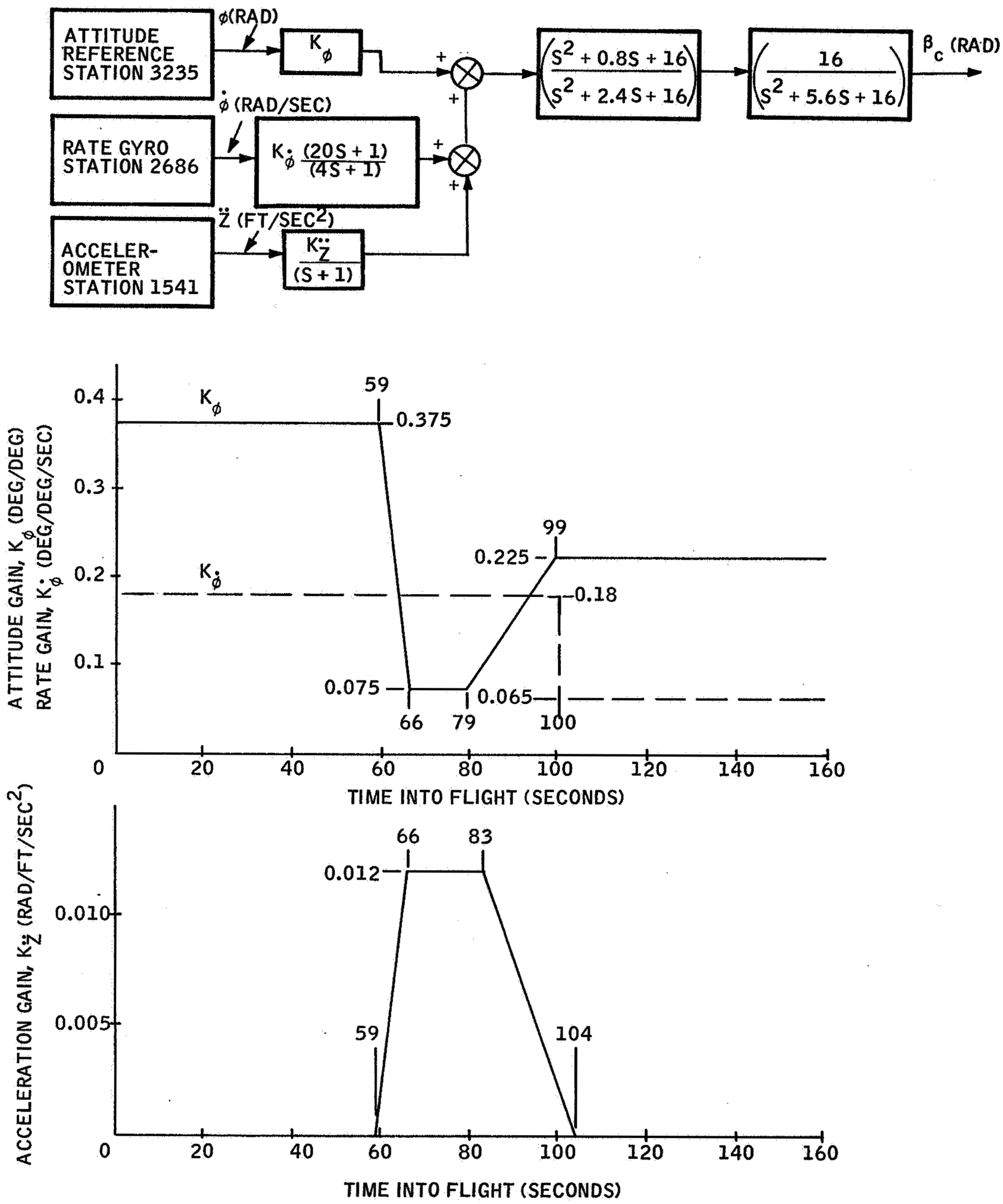


Figure 11. Saturn V/Voyager (73-foot payload) Modified LR-1 Attitude/Load Relief Controller Block Diagram and Gain Schedules

The forward loop gain schedule, $K_c(t)$, was eliminated in the modified LR-1 system. This change required further modification of the attitude gain schedule and a step change in the rate gain at 100 seconds. The attitude gain schedule was limited to 60 percent of the attitude gain at launch during the last 60 seconds of flight in order to meet stability requirements.

Trajectory and load data are presented in Table 6. This data shows that the modified LR-1 system met all terminal condition requirements and bending moment constraints.

Stability margins at three time points for the modified LR-1 system are presented in Table 7.

4.3 ANALYSIS OF PRELIMINARY LR-2

The preliminary LR-2 block diagram and associated gain schedules are shown in Figure 12. The important configuration changes include replacing the active filters with first-order lag filters and moving all filtering to the individual feedback paths. Replacing active filters with passive filters was accomplished by plotting frequency response characteristics of the active filters and then matching active filter characteristics as closely as possible with passive networks. The passive filter configuration was then placed on the individual feedback paths. Further stability analysis indicated that filtering could be removed from the attitude feedback loop.

All three gain schedules (K_ϕ, $K_{\dot{\phi}}$, and $K_{\ddot{z}}$) were modified somewhat to improve system stability. Stability margins for the preliminary LR-2 control system are presented in Table 8. These margins were considered acceptable even though it was desired to enhance gain and phase margins at the 92 and 100-second conditions.

Table 6. Summary of Booster Performance Data for Modified LR-1 Control System

Wind Condition and Type	Booster Performance Parameter			
	Station 3256 Max. Bending Moment (kg-m)	Angle of Attack at Burnout (deg)	Drift Rate at Burnout (m/s)	Drift at Burnout (km)
May - Dec Mach 1				
Yaw Wind	4.6	2.1	6.2	1.4
Tail Wind	4.4	1.0	18.3	1.6
Head Wind	4.0	0.6	10.7	0.0
May - Dec Max. $q\alpha$				
Yaw Wind	3.2	2.3	6.1	1.0
Tail Wind	3.1	1.0	18.3	1.4
Head Wind	2.9	0.5	6.0	0.2
May - Dec Max. q				
Yaw Wind	4.5	1.9	3.0	0.2
Tail Wind	3.5	0.7	12.2	1.0
Head Wind	3.4	0.5	15.2	0.6
May - Dec Reverse Shear				
Yaw Wind	3.9	1.0	7.6	1.2
Tail Wind	4.0	2.0	0.0	0.8
Head Wind	3.4	0.5	6.0	0.4

Table 7. Modified LR-1 Load Relief System Stability Margins

Time into Flight (sec)	Lower Gain Margin (db)	Phase Margin (deg)	Upper Gain Margin (db)	Phase Margin First Mode [1] (deg)
8.0	19.6	50.8	9.2	56.6
83.0	3.9	15.9	9.1	120.0
156.0	26.3	33.7	7.11	89.1

[1] Second, third, and fourth structural modes are gain-stabilized.

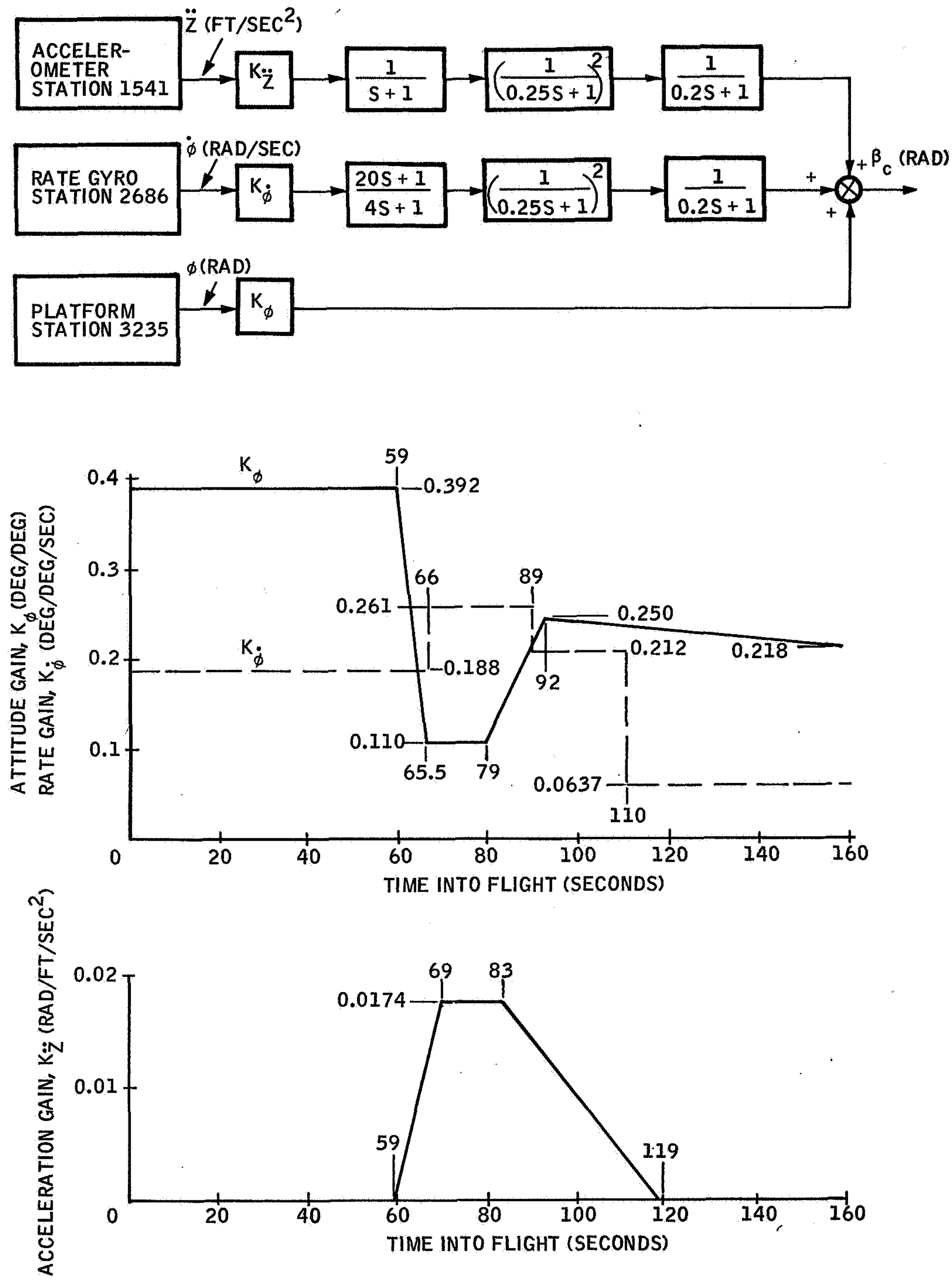


Figure 12. Saturn V/Voyager (73-foot payload) Preliminary LR-2 Load Relief Controller Block Diagram and Gain Schedules

Table 8. Stability Margins for Preliminary LR-2 Load Relief Control System on Saturn V/Voyager

Time into Flight (sec)	Lower Gain Margin (db)	Phase Margin (deg)	Upper Gain Margin (db)	Phase Margin First Mode$^{(1)}$ (deg)
8.0	21.7	42.8	8.5	125.7
40.0	15.0	42.2	6.7	148.9
60.0	13.3	43.0	7.3	166.0
64.0	15.0	50.3	7.7	160.1$^{(2)}$
72.0	12.3	43.2	6.5	(3)
83.0	6.8	30.2	6.0	(3)
92.0	6.0	25.2	6.7	158.3$^{(2)}$
100.0	5.9	36.2	5.7	180.0$^{(2)}$
120.0	7.4	32.8	7.5	99.2$^{(2)}$
156.0	30.3	30.0	6.2	69.5

(1) Second, third, and fourth structural modes gain-stabilized.

(2) First structural mode gain stable with less than 6 decibels margin.

(3) First structural mode gain-stabilized by 6 decibels.

Bending moment and trajectory data for the preliminary LR-2 control system are presented in Table 9. The performance data indicates that bending moment and trajectory requirements are met for the nominal vehicle configuration. Table 10 shows preliminary LR-2 performance in the presence of thrust misalignment. This data shows that the terminal condition drift rate exceeded the maximum allowable drift rate. As a consequence, a drift rate feedback would be required to reduce the terminal drift rate in the presence of thrust misalignment.

4.4 DEFINITION OF LR-2 CONTROL SYSTEM

As pointed out in the previous paragraphs, two deficiencies were evident in the preliminary LR-2 system. These were the excessive drift rate at burnout due to thrust misalignment and the acceptable but somewhat borderline stability margins at the high dynamic pressure conditions. The final step, then, in the definition of a load relief control system was to enhance stability margins and to correct the drift rate problem.

The drift rate problem at burnout was corrected by the addition of a drift rate feedback. This feedback signal was obtained from the platform.

Stability analyses conducted up to and including the analysis of the preliminary LR-2 system were minimal. As a consequence, it was not known if compensation in the preliminary LR-2 system was effective or not. In an effort to establish the effectiveness of the compensation and enhance stability margins, a systematic synthesis procedure was developed. The procedure provided a means of defining system compensation in terms of stability requirements. The advantage of the technique was that it provided the needed insight into the problem and eliminated most of the trial and error analysis generally required. The technique is described in Appendix E.

Table 9. Summary of Booster Performance Data for Preliminary LR-2 Load Relief Control System

Wind Condition and Type	Parameter			
	Station 3256 Max. Bending Moment (kg-m)	Angle of Attack at Burnout (deg)	Drift Rate at Burnout (m/s)	Drift at Burnout (km)
May - Dec Mach 1				
Yaw Wind	4.8	- 3.0	0.0	+ 1.4
Tail Wind	4.38	- 1.5	- 6.0	+ 1.8
Head Wind	4.40	+ 0.8	0.0	- 0.18
May - Dec Max. $q\alpha$				
Yaw Wind	3.9	- 2.5	+ 5.0	+ 0.8
Tail Wind	3.2	- 1.50	- 6.0	+ 1.6
Head Wind	3.4	+ 0.62	- 4.0	- 0.10
May - Dec Max. q				
Yaw Wind	4.3	- 2.0	- 6.0	+ 0.20
Tail Wind	3.8	- 1.5	- 5.0	+ 1.2
Head Wind	3.5	+ 1.0	- 4.0	+ 0.3
May - Dec Mach 2				
Yaw Wind	3.0	- 2.0	- 7.5	- 0.20
Tail Wind	2.8	- 1.4	- 6.0	+ 0.84
Head Wind	1.5	+ 0.5	0.0	+ 0.63
May - Dec Reverse Shear				
Yaw Wind	2.9	- 1.75	- 7.5	- 1.2
Tail Wind	3.2	- 1.5	+ 6.0	+ 1.6
Head Wind	2.7	+ 0.5	-18.0	0.0

Table 10. Summary of Booster Performance Data for Preliminary LR-2 System with ±0.38 degree Thrust Misalignment -- Maximum Annual Yaw Winds

Wind Condition and Type	Parameter			
	Station 3256 Max. Bending Moment (kg-m)	Angle of Attack at Burnout (deg)	Drift Rate at Burnout (m/s)	Drift Displacement (km)
Mach 1				
+0.38	5.1	-2.5	-68.0	-2.4
-0.38	5.0	-3.1	+99.0	+6.5
Max. $q\alpha$ Wind				
+0.38	4.6	-2.0	-75.1	-3.4
-0.38	4.1	-3.0	+87.0	+5.4
Max. q Wind				
+0.38	5.0	-2.75	+78	+4.6
-0.38	4.8	-2.00	-83	-4.0
Mach 2				
+0.38	3.0	-2.0	-65.0	-4.5
-0.38	3.7	-3.3	+71.0	+4.1
MSFC Reverse Shear				
+0.38	3.1	-1.5	-110	-7.0
-0.38	3.0	-2.5	+55	+2.1

Using the synthesis technique, an improved compensation was defined. As a result, the preliminary LR-2 system was modified by changing the compensation. In addition, a drift rate feedback was added to cope with the thrust misalignment problem. The new controller configuration, designated the LR-2 system, met all performance requirements and design constraints. The LR-2 system compensation was only slightly different from that of the preliminary LR-2 configuration; stability margins were improved; and the tolerance of the vehicle-system combination to uncertainties was increased over that of the preliminary LR-2 system.

The LR-2 is the recommended control system configuration for the Saturn V/Voyager application. A block diagram of this configuration is shown in Figure 1 in Section 1. The rationale behind the selection of each element forming this configuration is discussed in this section, along with nominal system performance and stability.

4.4.1 Attitude Feedback Elements

The attitude signal was obtained from the platform at station 3235, as specified by the design constraints. There was no frequency-dependent compensation required on the attitude feedback. Attitude gain, K_ϕ, however, was scheduled as a function of time.

In the period of flight when peak winds could be expected, attitude gain was reduced and acceleration gain was increased to change the system to a load relief function. Analysis has shown in past studies that the ratio of attitude gain, K_ϕ, to acceleration gain, K_z, largely determines system load reduction capability. There is a minimum value of attitude gain required, however, to assure acceptable terminal condition performance. Since K_ϕ and K_z affect system trajectory performance in a conflicting manner, the ratio was established (by tradeoff in a trajectory analysis) to minimize bending moment and burnout drift rates as much as possible. A gain of 0.095 degree per degree, between 65 and 80 seconds, was selected on the basis of time-varying simulation. Attitude gain during the last phase of flight was determined by stability margin requirements only.

Gain schedule breakpoints at 59 and 94 seconds were defined by the wind models specified by MSFC. These times were selected to encompass the model with early shear buildup, Mach 1, and the model with delayed buildup, Mach 2. The period of minimum attitude gain, 65 to 80 seconds, was defined by that time interval during boost flight when maximum aerodynamic loads are expected.

No attitude feedback signal shaping was required. The forward loop compensation of LR-1, relocated in the feedback paths according to directives, was eliminated from the attitude path. This improved system phase characteristics in the low-frequency range, thereby increasing phase margins at the rigid body.

4.4.2 Acceleration Feedback Elements

Placement of the accelerometer was determined by the following factors:

- The location of the instantaneous center of rotation
- The most forward center of gravity location
- The maximum gain as a function of sensor location which will meet the high-frequency gain margin constraint
- The allowable sensor mounting points as defined in Section 3.3.

It is desirable, for rigid-body stability reasons, to place the accelerometer ahead of the center of gravity. For increased load reduction capability, it is equally desirable to place the sensor at the instantaneous center of rotation for gimbal deflections in order to minimize gimbal deflection pickup and so as to sense primarily angle of attack. Of the available mounting fixtures, station 1541, the most aft location, was selected as it most closely matched the preferred locations. Station 1541 will be forward of the actual center of gravity position until 145.7 seconds into the flight.

Since an accelerometer is readily available on the platform, it would have been advantageous to have used this platform-mounted accelerometer instead of the additional body-mounted sensor required at 1541. This was investigated briefly in the study and is described in detail in Appendix B. A system was defined which used the platform-mounted accelerometer but, because of insufficient time, the design was not completed.

Acceleration gain for an accelerometer placed at 1541 was defined by the following constraints:

- The ratio of attitude gain to acceleration gain reached as a compromise between load reduction and terminal performance requirements

- The high-frequency gain margin requirement.

Once established, the attitude-to-acceleration gain ratio, coupled with a selected value of attitude gain, automatically determines acceleration gain for acceptable trajectory performance. To assure an adequate high-frequency stability margin, it was desirable to minimize acceleration gain.

Active filters of the LR-1 system designed to attenuate slosh mode pickup by both acceleration and rate sensors, and to provide required phase margin at the first bending mode were replaced with passive filters and relocated in the feedback paths in the LR-2 configuration. This was done to meet the design constraints stated in Section 3. 3. Elimination of the active notch filter improved both rigid-body and first-bending-mode phase margins.

When performing the synthesis of the LR-2 compensation, the filter time constant of the preliminary LR-2, a 1-second lag on acceleration, was reduced to the more optimum value of 0. 5 to widen the phase constraints governing rate compensation design. This also relaxed the high-frequency constraints on maximum allowable rate gain. The filter $(1/0.167S + 1)$ was added for the same reasons and served to improve system tolerance to parameter uncertainties.

4. 4. 3 Attitude Rate Feedback Elements

The attitude rate gyro was placed at station 2747 in the previous Saturn V/ Voyager study based on flexible vehicle analysis. Gyro station 2686 was selected for the LR-2 because it was the closest available mounting to 2747. Subsequent analyses did not indicate a need to change this location.

Rate gain throughout first-stage flight was determined by the stability margin requirements of Section 3. 2. A discontinuous schedule of gain was used since design constraints directed that only two gains could be scheduled continuously with time. Breakpoints 66, 98, and 110 were selected to optimize system tolerance to parameter uncertainties.

Rate compensation was designed to meet filter phase and gain constraints defined by the synthesis approach at the critical flight times between maximum q and 120 seconds. Lead lag filter $\frac{3S + 1}{1.2S + 1}$ replaced the $\frac{20S + 1}{4S + 1}$

used for the LR-1 in order to relax the upper bound on rate gain and to improve tolerance to parameter variations. The 0.2-second lag used in the preliminary LR-2 system was changed to 0.286 second to enhance the high-frequency gain margin.

4.4.4 Drift Rate Feedback Elements

The drift rate signal used to reduce terminal drift rates in the presence of thrust misalignments was obtained from platform station 3235. The signal is obtained by integrating the ratio of normal acceleration to axial acceleration. This integrated signal is readily available since it is required by upper-stage control for the same purpose. It therefore did not introduce additional complexity to generate the signal for the LR-2 configuration.

The amount of drift rate compensation required was established by trajectory analysis considering the most severe winds with thrust misalignment. Based on trajectory analysis, a fixed value of 0.007 second was selected. The signal is summed on the platform with attitude to feed back upstream of the attitude gain element. By scheduling with attitude gain, the adverse effect of drift rate feedback on load reduction capability was minimized when attitude gain was reduced. This is evidenced by Table 11, which presents LR-2 performance data with and without compensation included. As noted, under most situations critical loads at station 3256 are unchanged. The only exception is Mach 1 wind disturbance, where the bending moment is increased to 5.0×10^5 kg-m. This is within the allowable limit of 5.4×10^5 kg-m.

The only parameter uncertainty with significant effect on terminal drift rate is thrust misalignment. Without drift compensation the allowable drift rate limit with thrust misalignment was exceeded for all but a few situations, as indicated by the data in Table 11. On the other hand, when drift rate feedback was added, burnout drift rates were reduced to less than 70 meters per second in all but one case, maximum $q\alpha$. This drift rate was 74.0 meters per second.

Table 11. Performance Data for LR-2 Load Relief Control System With and Without Drift Rate Compensation

Wind Disturbance Model	Thrust Misalignment (deg)	Maximum Binding Moment at Station 3256 (10^5 kg - m)		Drift Rate at Burnout (m/s)	
		$K_{\dot{z}} = 0$	$K_{\dot{z}} = 7x10^{-3}$ sec	$K_{\dot{z}} = 0$	$K_{\dot{z}} = 7x10^{-3}$ sec
Mach 1	+ 0.38	4.8	4.7	-104.8	-68.0
Max. q α	+ 0.38	4.5	4.6	-105.0	-74.0
Max. q	+ 0.38	4.6	4.6	-100.0	-60.0
Mach 2	+ 0.38	2.4	2.4	-107.0	-70.0
Reverse Shear	+ 0.38	2.9	2.9	-118.0	-57.0
Mach 1	- 0.38	4.2	5.0	85.9	43.0
Max. q α	- 0.38	4.2	4.6	88.0	43.2
Max. q	- 0.38	4.7	4.7	67.0	35.0
Mach 2	- 0.38	3.5	3.4	55.0	36.0
Reverse Shear	- 0.38	3.8	3.7	40.0	32.0

The penalty paid for introducing a drift rate signal was a slight reduction in the lower gain margins. Table 12 presents stability margins for the LR-2 with and without drift rate compensation. Although rigid-body margins are decreased slightly, they do not fall below the constraints stipulated by NASA. Data at the first bending mode was not given, as drift rate affects only rigid-body frequencies. This is evidenced by the upper gain margin data.

4.5 PERFORMANCE EVALUATION

A stability analysis of the LR-2 system was conducted at 10 selected time points during first-stage flight. These points are representative of the extremes expected. Stability data obtained during the analysis is presented in Appendix C in root locus form by Figures C1 through C10 and in frequency response form by Figures C11 through C20.

To evaluate the stability data, a summary table comparing stability margins achieved against the requirements (stated in Section 3.2) is presented in Table 12. As indicated, acceptable stability margins are exhibited at all time points.

Performance of the Saturn V/Voyager with the LR-2 system during first-stage flight when subjected to maximum annual and maximum mission (May-December) winds was simulated by both analog and digital time-varying flight simulation programs. Analog traces obtained of the nominal system response to maximum-mission wind models are included in Appendix D, Figures D1 through D4. Tables 13 and 14 summarize trajectory performance with both maximum annual and maximum mission winds and compare this performance with stated performance requirements. As shown, all requirements are met for the most severe wind models. Bending loads at other than critical station (3256) are also shown to be far below the maximum allowable levels.

Table 12. Stability Margin Data for LR-2 Load Relief Control System with and without Drift Rate Feedback

Time Into Flight (sec)	Lower Gain Margin (db)		Phase Margin (deg)		Upper Gain Margin (db)	
	$K_{\dot{z}} = 0$	$K_{\dot{z}} = 7x10^{-3}$	$K_{\dot{z}} = 0$	$K_{\dot{z}} = 7x10^{-3}$ sec	$K_{\dot{z}} = 0$	$K_{\dot{z}} = 7x10^{-3}$ sec
8.0	22.0	21.2	50.5	49.9	8.3	8.3
40.0	14.5	14.1	50.6	49.7	6.5	6.5
60.0	13.0	12.6	50.9	50.4	6.1	6.1
64.0	14.8	14.6	55.4	55.2	9.0	9.0
72.0	13.5	13.4	44.1	44.0	8.1	8.1
83.0	8.4	8.2	31.0	30.8	7.7	7.7
92.0	8.1	7.8	32.9	32.6	6.6	6.6
100.0	6.4	6.1	31.0	30.5	8.1	8.1
120.0	7.4	6.9	31.0	30.0	7.0	7.0
156.0	30.2	27.6	40.2	40.2	6.1	6.1

Table 13. Performance Summary for Saturn V/Voyager with LR-2 Control System -- Maximum Annual Yaw Winds

Wind Model	Peak Bending Moments (10^5 kg - m)				Conditions at Burnout		
	Station 3256	Station 2747	Station 2519	Station 1541	Angle of Attack (deg)	Drift Rate (m/s)	Drift Displacement (km)
Mach 1	4.8	8.83	9.85	17.97	-2.05	-15.4	0.44
Max. $q\alpha$	4.6	7.36	8.15	16.34	-2.0	-15.6	0.25
Max. q	4.6	8.25	8.3	16.3	-1.9	-16.5	-0.23
Mach 2	2.9	7.11	7.3	12.9	-2.1	-15.0	-0.50
Reverse Shear	3.1	5.23	6.3	11.64	-1.78	-14.1	-1.48
Measured No. 1639	3.6	6.37	7.6	13.72	-1.19	- 5.8	-0.15
No. 515-06	3.0	5.19	6.3	11.61	-1.09	- 7.4	-0.47
Required	5.4	11.5	20.5	59.0	±3.4	±70.0	±30.0

Table 14. Performance Summary for Saturn V/Voyager with LR-2 Control System -- Maximum Mission (May-Dec Winds)

Wind Model	Direction of Wind	Peak Bending Moment Station 3256 (10^5 kg-m)	Conditions at Burnout		
			Angle of Attack (deg)	Drift Rate (m/s)	Drift (km)
Mach 1	Yaw	4.6	-2.0	-14.0	0.42
	Head	4.2	1.0	1.0	0.25
	Tail	4.0	-1.0	-25.0	1.00
Max. $q\alpha$	Yaw	4.0	-1.9	-11.0	0.28
	Head	3.8	1.5	9.0	---
	Tail	3.35	-0.7	-19.0	1.00
Max. q	Yaw	4.1	-1.6	-15.0	-0.42
	Head	3.4	0.65	-11.0	0.50
	Tail	3.0	-0.9	-20.0	0.70
Mach 2	Yaw	2.5	-1.5	-15.0	-0.70
	Head	1.4	0.5	-12.5	0.60
	Tail	2.3	-0.95	-20.0	0.50
Reverse Shear	Yaw	2.75	-1.5	-11.0	-1.65
	Head	2.60	0.7	-30.0	-0.35
	Tail	2.80	-1.0	-5.0	1.20
Requirement	---	5.4	±3.4	±70.0	±30.0

After the LR-2 nominal trajectory performance and stability margins had been determined, a parameter variation study was performed to evaluate the effects of the parameter variations listed in Section 3.4. Results are summarized in Tables 15 and 16 for trajectory and stability margin variations, respectively.

Table 15 summarizes peak bending loads and burnout conditions which occur when individual parameters are varied. Deviations from nominal performance were root-summed-squared to define the maximum probable deviation interval about nominal. Of the trajectory parameters of interest, only burnout drift rate of -71.8 meters per second would exceed the allowable level when maximum deviation occurred. This was considered acceptable.

Table 16 lists nominal stability margins, together with maximum deviations obtained in the stability margins for all parameter variations considered, at the 10 selected flight times. The maximum deviation was computed by combining deviations in gain and phase caused by individual parameter uncertainties in the conventional rss manner. At no time point did the combined error produce an unstable vehicle. The minimum margin that could occur would be a 3.58-decibel upper gain margin at 92 seconds into the flight and 18.62 degrees phase margin at 83 seconds (maximum q) into the flight. This will not seriously degrade system response.

Table 15. Summary Performance Variation Due to LR-2 and Saturn V/Voyager Parameter Uncertainties

Parameter Uncertainty		Peak Bending Moment, Station 3256 (10^5 kg-m)	Conditions at Burnout: Angle of Attack (deg)	Drift Rate (m/s)	Drift Displacement (km)
Nominal Plus RSS of Variation in Performance[1]		4.0 +0.82 -0.41	-1.9 +0.75 -1.02	-11.0 +55.4 -60.8	0.28 +3.05 -4.41
Aerodynamic					
C_{N_α}	+10%	4.07	-1.5	-13.5	0
	-10%	4.18	-1.75	- 8.1	0.40
Moment Arm:	+127"	4.1	-1.57	-19.6	-4.15
	-127"	3.95	-2.0	12.7	0.23
Thrust					
Magnitude:	+1.5%	4.1	-1.6	-10.2	0.30
	-1.5%	4.1	-1.6	- 9.0	0.05
Alignment:	+0.38°	4.0	-1.82	-69.4	-3.17
	-0.38°	4.0	-1.99	47.8	3.73
Control System Gains					
K_Φ	+10%	4.2	-1.8	- 8.0	0.23
	-10%	4.0	-1.5	-13.0	0.18
$K_{\ddot{Z}}$	+10%	3.9	-2.0	- 8.0	0.60
	-10%	4.22	-1.6	-12.0	0.10
Schedule:	t+5 sec	4.6	-1.7	-15.0	0
	t-5 sec	4.45	-2.0	-11.0	0.20
Bending Frequencies					
	+20%	4.1	-1.9	- 9.0	0.30
	-20%	4.05	-2.0	-10.5	0.20

[1] All data obtained for max. $q\alpha$ yaw wind, maximum mission model.

Table 16. Variation[1] in Stability Margins Due to LR-2 and Saturn V/Voyager Parameter Uncertainties

Time Info Flight (sec)	Lower Gain Margin (db)	Phase Margin (deg)	Upper Gain Margin (db)
Required	6.0	30.0	6.0
8.0	21.4 + 2.19 - 1.52	50.2 + 2.44 - 2.36	8.3 +1.17 -1.53
40.0	14.2 + 3.34 - 2.36	49.7 + 3.18 - 2.78	6.5 +1.07 -1.68
60.0	12.7 + 8.0 - 3.95	50.6 + 6.32 - 4.19	6.1 +4.55 -1.68
64.0	14.7 +24.85 - 5.38	55.2 + 3.46 -11.18	9.0 +1.46 -4.10
72.0	13.4 + 4.38 - 3.60	44.0 + 4.15 - 5.99	8.1 +7.9 -2.61
83.0	8.3 + 1.87 - 1.96	30.8 + 9.61 -12.18	7.7 +1.23 -1.45
92.0	7.9 + 1.39 - 1.64	32.7 + 3.22 - 6.80	6.6 +2.04 -3.02
100.0	6.2 + 2.60 - 2.26	30.7 +14.85 - 8.68	8.1 +1.61 -3.79
120.0	7.1 + 1.66 - 1.63	30.3 + 4.72 - 4.34	7.0 +1.20 -1.45
156.0	28.3 + 3.46 - 2.36	40.2 + 2.62 - 2.66	6.1 +0.80 -1.04

[1] Variations expressed are the RSS of variations induced by individual parameter uncertainties.

SECTION 5
REFERENCES

1) Honeywell Final Report 12003-SV6, "A Load Relief Control System for the S-1C Stage of the Saturn V with Voyager Payload", 10 January 1967, prepared for NASA-MSFC, Contract NAS8-11206, Mod. 5.

2) Honeywell Final Report 21171-SR1, "Data Base Report for Saturn V/ Voyager Load Relief Study", 15 September 1967 (updated 30 January 1968), prepared for NASA-MSFC, Contract NAS8-21171.

APPENDIX A

MODIFICATION OF PRESENT SATURN/APOLLO CONTROL SYSTEM WITH VOYAGER PAYLOAD

In a brief analysis the present Saturn/Apollo control system was modified by the addition of a body-mounted accelerometer to provide a load relief capability. This analysis was done to determine if the current Apollo system could be simply modified to provide acceptable load relief. The time-varying analog computer simulation was used to determine feedback gain schedules that would result in acceptable load relief and trajectory performance. Attitude and acceleration gain schedules are identical to those given for the modified LR-1 load relief control system. The rate gain was not modified.

The configuration, with the added accelerometer feedback loop and revised gain schedules, was designated the modified Apollo control system.

A block diagram and associated gain schedules of the above control system are presented in Figure A1. Loads and trajectory data are presented in Table A1. The data presented in Table A1 meets all bending moment and trajectory requirements.

Stability data for the modified Apollo configuration is presented in Table A2. Gain and phase margin requirements are not met at the 83-second time point. No attempt was made to improve existing gain and phase margins due to time limitations.

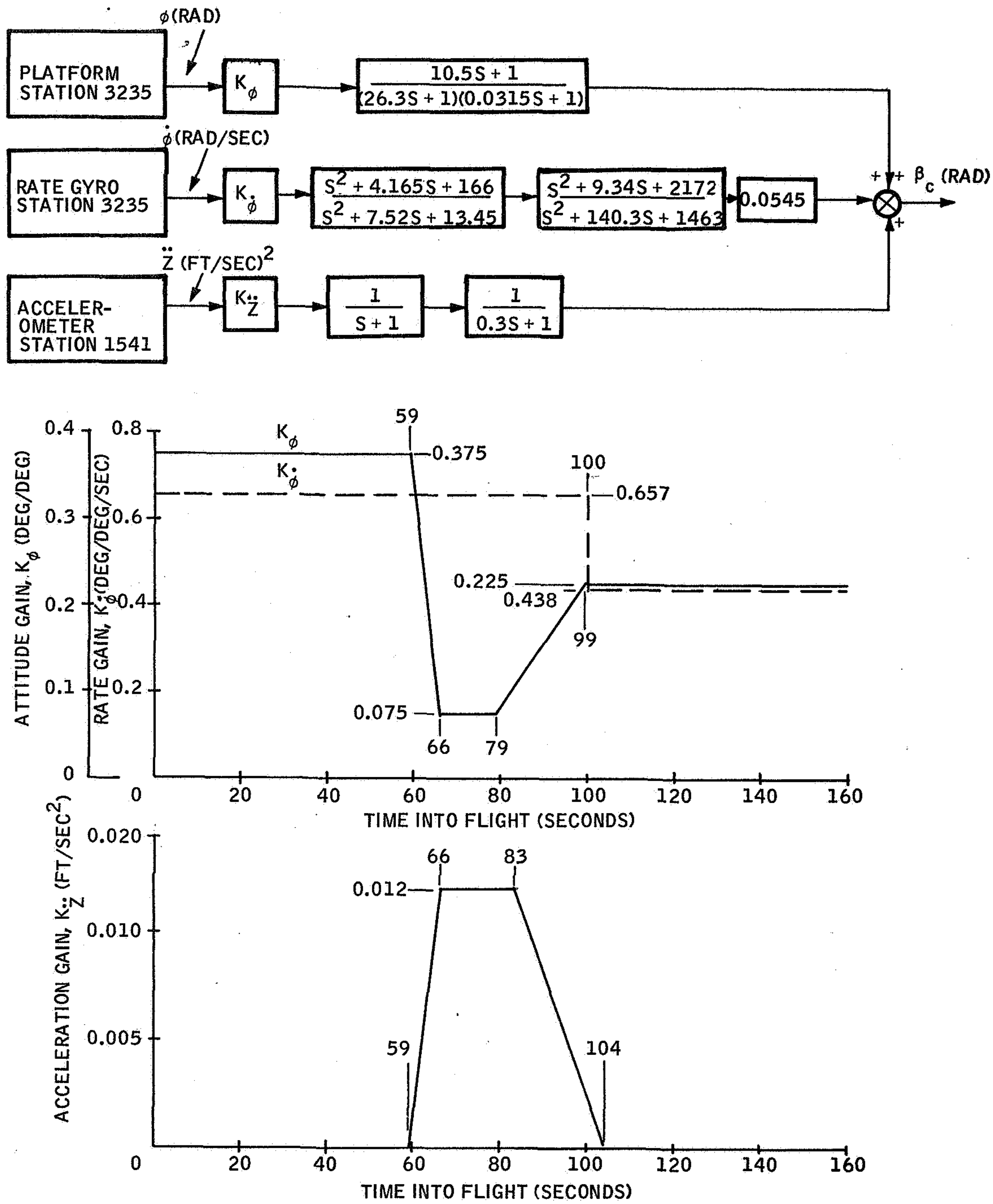


Figure A1. Saturn V/Voyager (70-foot payload) Modified Apollo (Mod AS 503) Attitude/Load Relief Controller Block Diagram and Gain Schedules

Table A1. Bending Moment and Trajectory Data for Modified Apollo Configuration

Yaw Wind Condition	Parameter			
	Maximum Bending Moment, Station 3256 (kg-m)	Angle of Attack at Burnout (deg)	Drift Rate at Burnout (m/s)	Drift Displacement at Burnout (km)
May-Dec. Mach 1	4.7	2.5	36.6	2.8
May-Dec. Max. $q\alpha$	4.2	2.0	43.0	3.0
May-Dec. Max. q	4.9	1.8	15.2	1.2
May-Dec. Mach 2	3.4	2.5	0	0.2

Table A2. Stability Data for Modified Apollo Configuration

Time Into Flight (sec)	Lower Gain Margin (db)	Phase Margin (deg)	Upper Gain Margin (db)	Phase Margin First Mode(1) (deg)
8	16.5	49.2	12.6	89.8
83	5.5	12.7	7.8	177.7
156	24.5	38.9	6.7	86.8

(1)Second, third, and fourth structural modes are gain-stabilized.

APPENDIX B

SATURN V/VOYAGER LOAD RELIEF STUDY USING PLATFORM-MOUNTED ACCELEROMETER

INTRODUCTION

During the 7 November 1967 coordination meeting held at MSFC, Honeywell agreed to evaluate the use of a platform-mounted accelerometer for load relief of the Saturn V/Voyager if time permitted. This appendix documents the results of that study.

SUMMARY

Based on a limited study performed in parallel with the contractual Saturn V/Voyager study it was concluded that use of a platform-mounted accelerometer in lieu of a body-mounted sensor was feasible. Several disadvantages if the sensor were relocated were cited, however, which should disqualify the platform-mounted accelerometer approach for consideration. Foremost among these are:

- The increase in system configuration complexity
- The degradation of annual wind terminal condition performance
- The "tailor fitting" of gain schedules to meet stability margin constraints

The limited amount of analysis performed during this study should be emphasized. With additional effort a more satisfactory system could have been defined.

Figure B1 is a block diagram of the preliminary system configuration. Performance of this system on the Saturn V/Voyager when subjected to maximum "q" wind profile disturbances, maximum annual and maximum mission (May-December launch period), is presented in Table B1. Bending moment requirements are met throughout first-stage flight. Terminal condition requirements, when a three-sigma uncertainty in thrust alignment is accounted for, are exceeded. Redesign of drift compensation should minimize this however.

System stability is summarized in Table B2. Adequate stability is achieved, but insufficient gain margins at two conditions, 92 and 120 seconds into flight, are exhibited.

PROBLEM DEFINITION

Performance requirements and design constraints imposed on Saturn V/Voyager design are applicable in this study. Stated in Section 3 of this report, they form the basis for evaluating the platform-mounted accelerometer.

The wind disturbances used for this study were the maximum mission (May-December launch period) and maximum annual synthetic wind profiles with maximum "q" shear buildup (Figures 4 and 5 of main text Reference 2). These were selected because they generate large bending moment loads, drift rates, and angles of attack when applied to the candidate control system, preliminary LR-2.

The only parameter uncertainty considered was thrust misalignment. Data in Section 4 shows other uncertainties to have negligible affect on system performance.

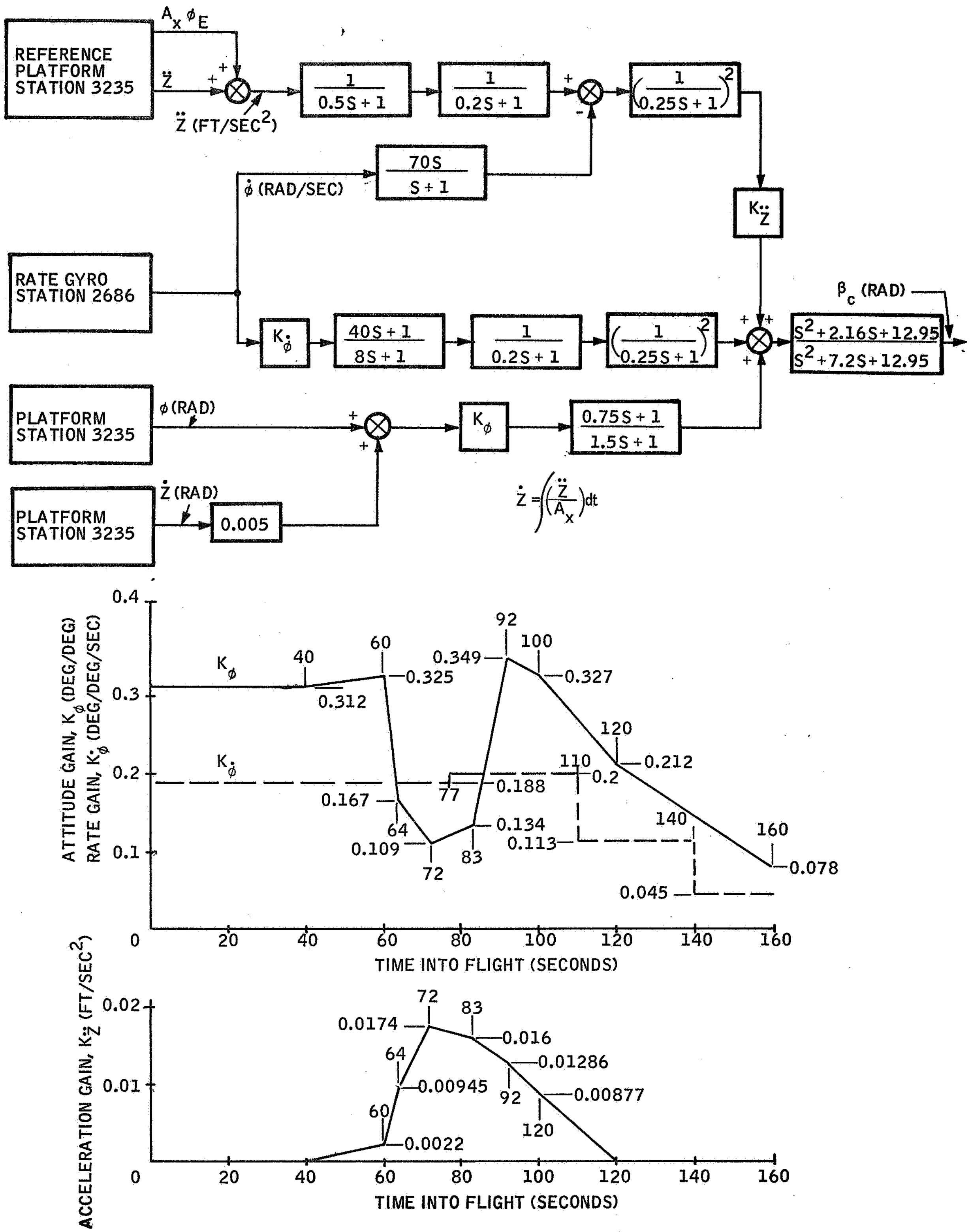


Figure B1. Saturn V/Voyager Load Relief Control System with Platform-Mounted Accelerometers

Table B1. Requirements and Performance Capabilities for Preliminary System Configuration

Wind Model	Thrust Misalignment (0.38 deg)	Drift Compensation	Bending Moment, Station 3256 (kg-m)	Angle of Attack at Burnout (deg)	Drift at Burnout (km)	Drift Rate at Burnout (m/s)
Annual Max. q	Yes	Yes	-4.89×10^5	-3.37	- 4.165	-102.5
Annual Max. q	Yes	No	-4.85×10^5	-3.58	- 5.278	-132.2
Annual Max. q	No	No	-4.99×10^5	-2.19	- 0.154	- 16.0
Annual Max. q	No	Yes	-5.04×10^5	-2.09	- 0.136	- 15.5
May-Dec. Max. q	Yes	Yes	-4.36×10^5	-3.15	- 4.224	-101.8
May-Dec. Max. q	Yes	No	-4.33×10^5	-3.37	- 5.343	-132.1
May-Dec. Max. q	No	No	-4.48×10^5	-1.95	- 0.220	- 15.9
Requirement	---	---	$\pm 5.4 \times 10^5$	±3.4	±30.0	± 70.0

Table B2. System Stability Margins

Flight Condition	Drift Compensation			No Drift Compensation		
	Lower Gain Margin (db)	Phase Margin (deg)	Upper Gain Margin (db)	Lower Gain Margin (db)	Phase Margin (deg)	Upper Gain Margin (db)
8 sec - Rigid Body	18.9	31	7.8	19.5	31	7.8
- Elastic Mode	---	---	---	---	---	---
40 sec - Rigid Body	12.0	31	7.5	12.3	31	7.5
- Elastic Mode	---	---	---	---	---	---
60 sec - Rigid Body	11.6	35	7.9	11.8	35	7.9
- Elastic Mode	---	---	---	---	---	---
64 sec - Rigid Body	13.9	51	8.4	14.1	50	8.4
- Elastic Mode	---	163	---	---	164	---
72 sec - Rigid Body	11.1	42	7.5	11.2	42	7.7
- Elastic Mode	---	110	---	---	106	---
83 sec - Rigid Body	6.0	39	6.2	6.1	39	6.2
- Elastic Mode	---	104	---	---	106	---
92 sec - Rigid Body	5.8	37	5.8	6.0	39	5.8
- Elastic Mode	---	128	---	---	128	---
100 sec - Rigid Body	6.0	37	6.1	6.2	37	6.1
- Elastic Mode	---	145	---	---	145	---
120 sec - Rigid Body	5.9	30	7.7	6.1	30	7.7
- Elastic Mode	---	---	---	---	---	---
156 sec - Rigid Body	19.4	34	10.2	21.0	34	10.0
- Elastic Mode	---	---	---	---	---	---

DEFINITION OF CANDIDATE CONTROL SYSTEM

Figure 1 of the main text shows the block diagram and gain schedules of a modified preliminary LR-2 control system configuration. This configuration, with a platform-mounted accelerometer replacing the body-mounted sensor, was, by definition, designated the candidate control system. The preliminary LR-2 system was selected because it most nearly met the design requirements of the Saturn V/Voyager study prior to the start of this parallel sensor evaluation.

DEFINITION OF CONTROL SYSTEM CONFIGURATION

Relocation of the accelerometer from station 1541 to the guidance platform (station 3235) resulted in destabilizing the system by: (1) Introducing an additional rigid-body mode, called the "center of percussion" mode, which emerged at roughly 0.9 rad/sec and coupled with the slosh modes; and (2) Increasing high-frequency gain.

These effects were evident when Nyquist plots (Figures B2 and B3) of preliminary LR-2 system stability before and after sensor relocation were compared. To stabilize the system, it was necessary to suppress the new rigid-body mode and the existing slosh modes. No action on bending mode attenuation was necessary, however, since bending modes were either phase or gain-stabilized.

To attenuate slosh and percussion modes a shaped inverted rate signal was introduced and summed with the platform accelerometer signal. A passive notch filter on the summed signal to gimbal actuator was also inserted to further attenuate slosh modes so that acceptable stability margins could be

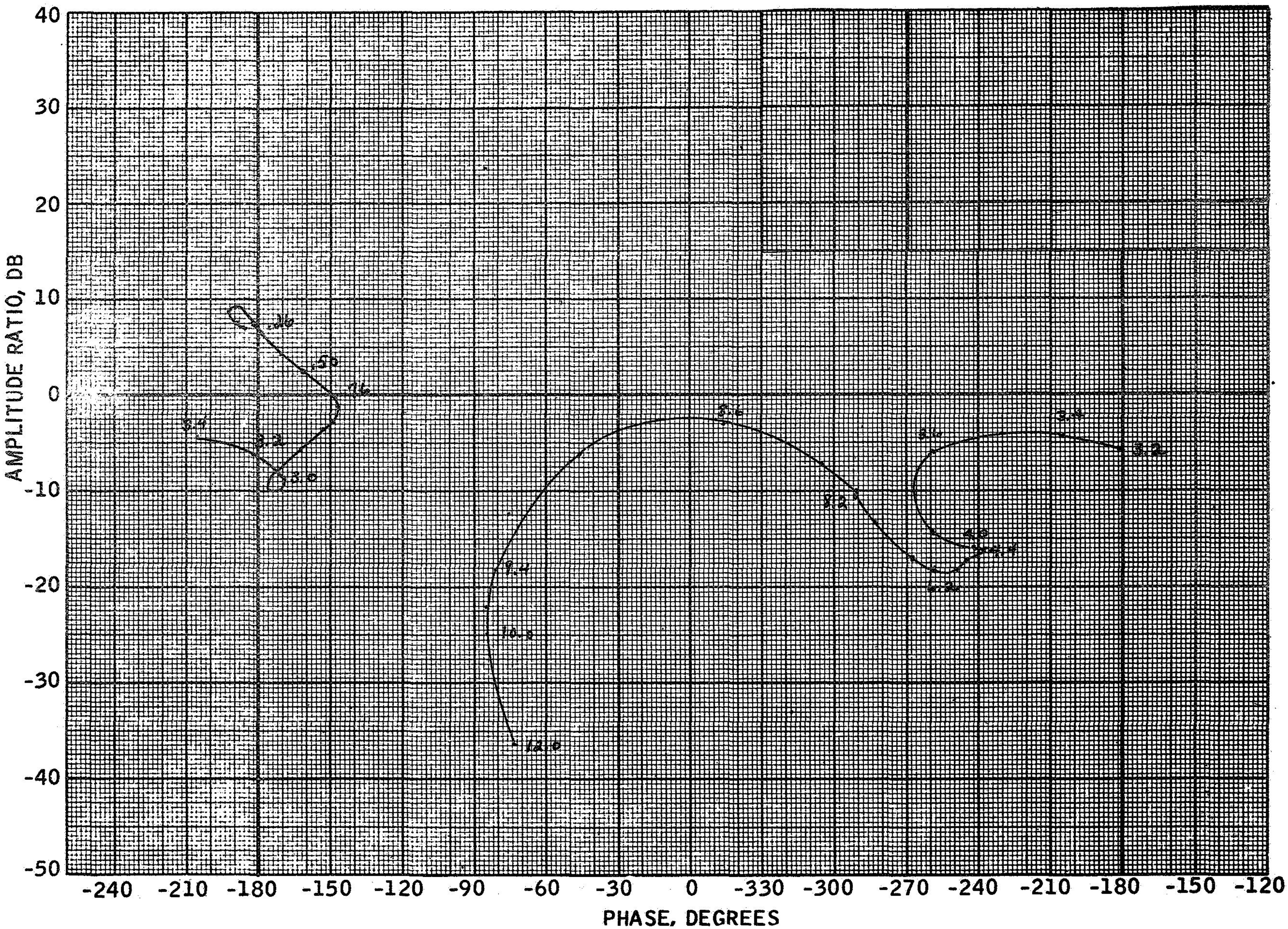


Figure B2. LR-2 Load Relief Control System -- 83-Second Flight Condition, Accelerometer Station 1541

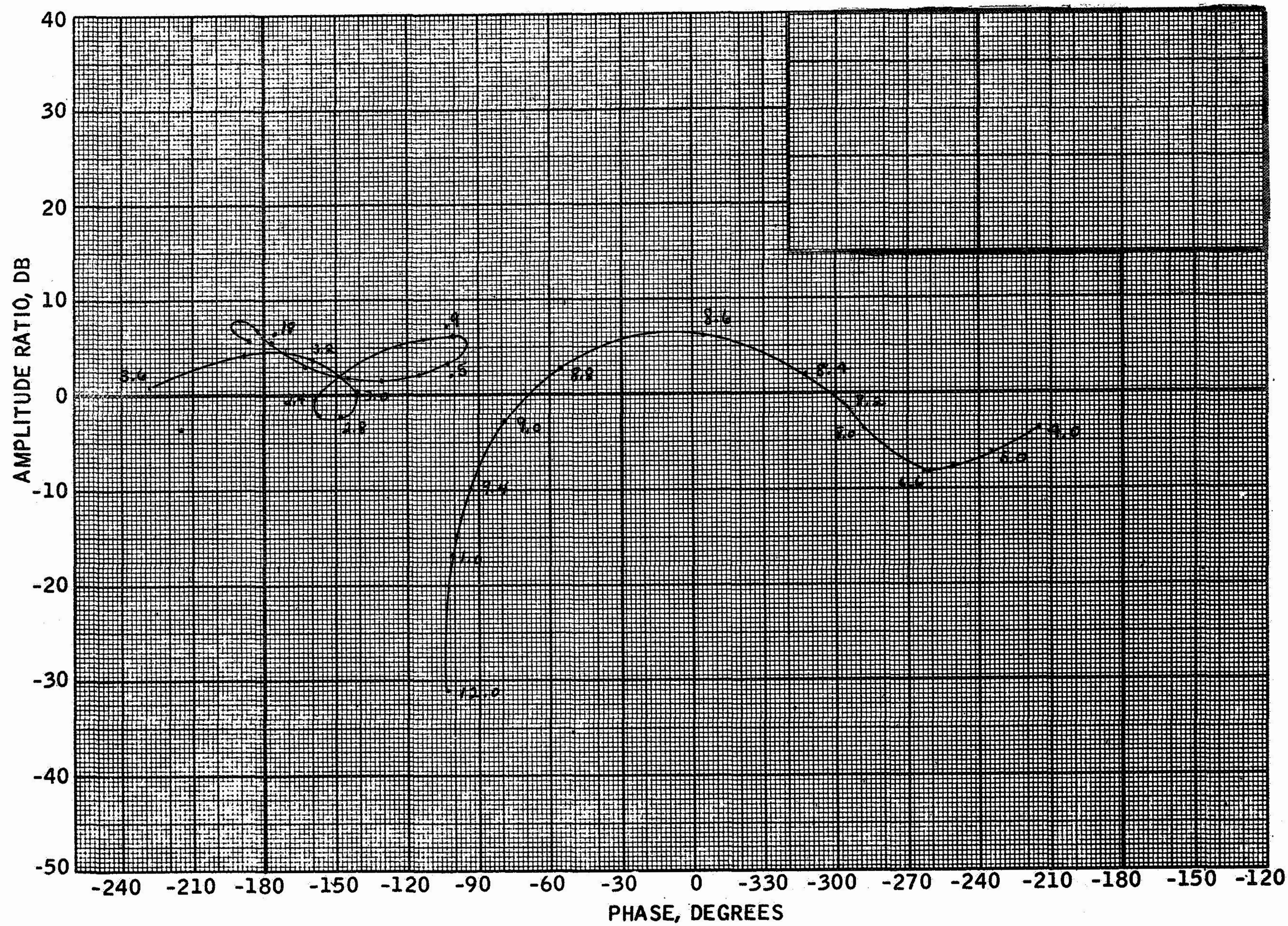


Figure B3. LR-2 Load Relief Control System -- 83-Second Flight Condition, Accelerometer Station 3235 achieved. To improve low-frequency response and provide increased decreasing gain margin, an attitude error signal, $A_x\phi E$, was added to the accelerometer signal. A brief analysis showed a requirement for this signal which, with further study of attitude loop shaping, could be eliminated.

Drift compensation developed for the LR-2 was used to reduce terminal drift rate and angle of attack. The amount of compensation is inadequate, as shown by terminal performance in Table B1; with additional analysis, however, a similar compensation technique could have been developed.

Figure B1 is a block diagram of the configuration defined to provide adequate performance and meet design constraints when the accelerometer sensor is located on the guidance platform. Tables B1 and B2 summarize the performance and stability margins by this configuration.

CONTROL SYSTEM PERFORMANCE

An accelerometer sensor is generally placed: (1) ahead of the center of gravity for rigid-body stability reasons, and (2) at the instantaneous center of rotation to minimize gimbal pickup and maximize the primary signal required for weather cocking and angle of attack.

Since the Saturn V/Voyager has a c.g. travel of 556 inches from station 1170 to station 1726 during first-stage flight, station 1541 was selected as the only mounting available which would meet these requirements.

Moving the accelerometer forward to station 3235 violated these requirements, resulting in:

- Decreased maximum stable forward loop gain
- Increased bending moment
- Decreased vehicle weather-cocking capability

The problem of gain increase resulted in an increase in system complexity in order to meet stability margin requirements. This contradicted the expressed design philosophy of a simplified LR-1 load relief control system. Stability margins were met, however, with the exception of decreasing gain margins at 92 and 100 seconds. These were adequate at 5.8 and 5.9 db, respectively, as shown in Table B2.

For maximum mission wind, bending moment load at the critical station 3256 was increased to 4.48×10^5 kg-m by moving the accelerometer to the platform mounting. This is within the performance requirement. An additional increase for thrust misalignment with adverse sign should not exceed the allowable 5.4×10^5 kg-m load. With maximum annual winds, a similar donclusion is reached as evidenced by performance data given in Table B1.

Reduction of the amount of weather cocking attributed to moving the sensor forward would have resulted in larger bending moments if drift rate downstream had not been increased. Drift rates with thrust alignment uncertainty taken into account exceed terminal condition requirements for both maximum mission and maximum annual winds. From Table B1 drift rate with compensation is 101.8 meters per second downstream, as opposed to the 70 meters per second allowable. With better drift compensation, however, this could be reduced, and in the process, angle of attack, marginal for maximum annual with misalignment, would also be reduced.

The price paid for increased drift compensation would be reduced lower gain margins as illustrated by Table B2. This is not considered a significant problem though, since maximum decrease is only about 0.2 db out of 6 db.

Of more significance is the manner in which the system stability margins were obtained. Only through "tailoring" of the gain schedules given on Figure B1 was this achieved. This again increased system complexity, which is objectionable under ground rules established for the Saturn V/Voyager study.

RECOMMENDATIONS

If further analysis on a platform-mounted accelerometer is undertaken, the following areas should be investigated:

- Reduction of system complexity

  a) Elimination of $A_X \phi_E$ attitude feedback

  b) Relocation of notch filter to feedback paths to satisfy design constraints

  c) Simplification of gain schedules

  d) Elimination of destabilizing rate feedback through acceleration signal loop

- Improvement of drift compensation

- Performance when subjected to other winds which have proven to be more severe in some instances, depending on the control system configuration

APPENDIX C

FREQUENCY RESPONSE AND ROOT LOCUS PLOTS FOR RECOMMENDED LR-2 LOAD RELIEF CONTROL SYSTEM

Root locus plots for the recommended LR-2 load relief control system are presented as Figures C1 through C10 for 10 flight conditions; i. e., 8, 40, 60, 64, 72, 83, 92, 100, 120, and 156 seconds into the flight. Gain 1.0 on each plot represents system nominal gain as given in the gain schedule in Figure 1 of the main text.

Frequency response plots at flight conditions corresponding to the root locus plots are given for the LR-2 system as Figures C11 through C20.

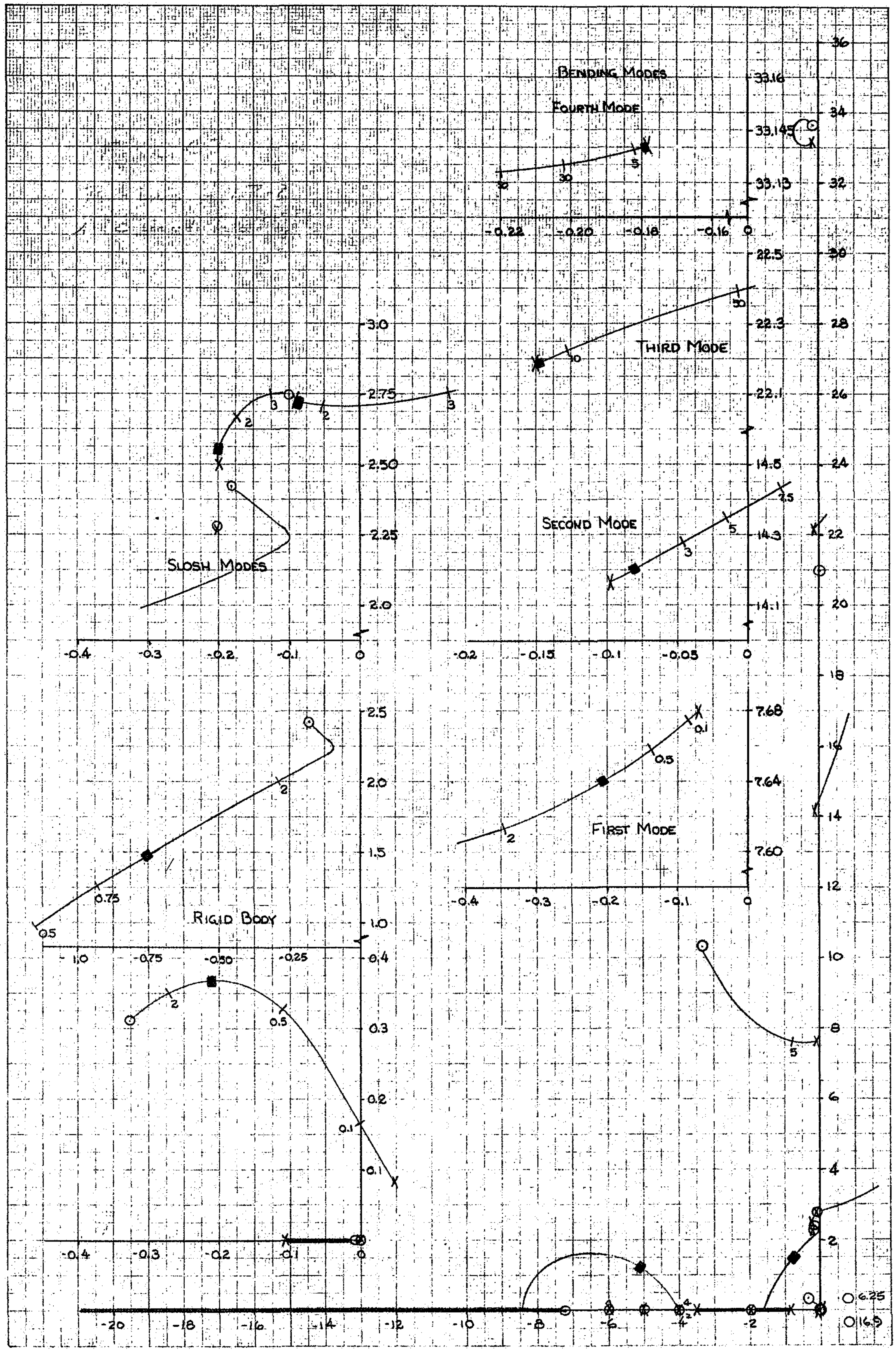


Figure C1. Root Locus Plot of LR-2 at Eight Seconds into Flight

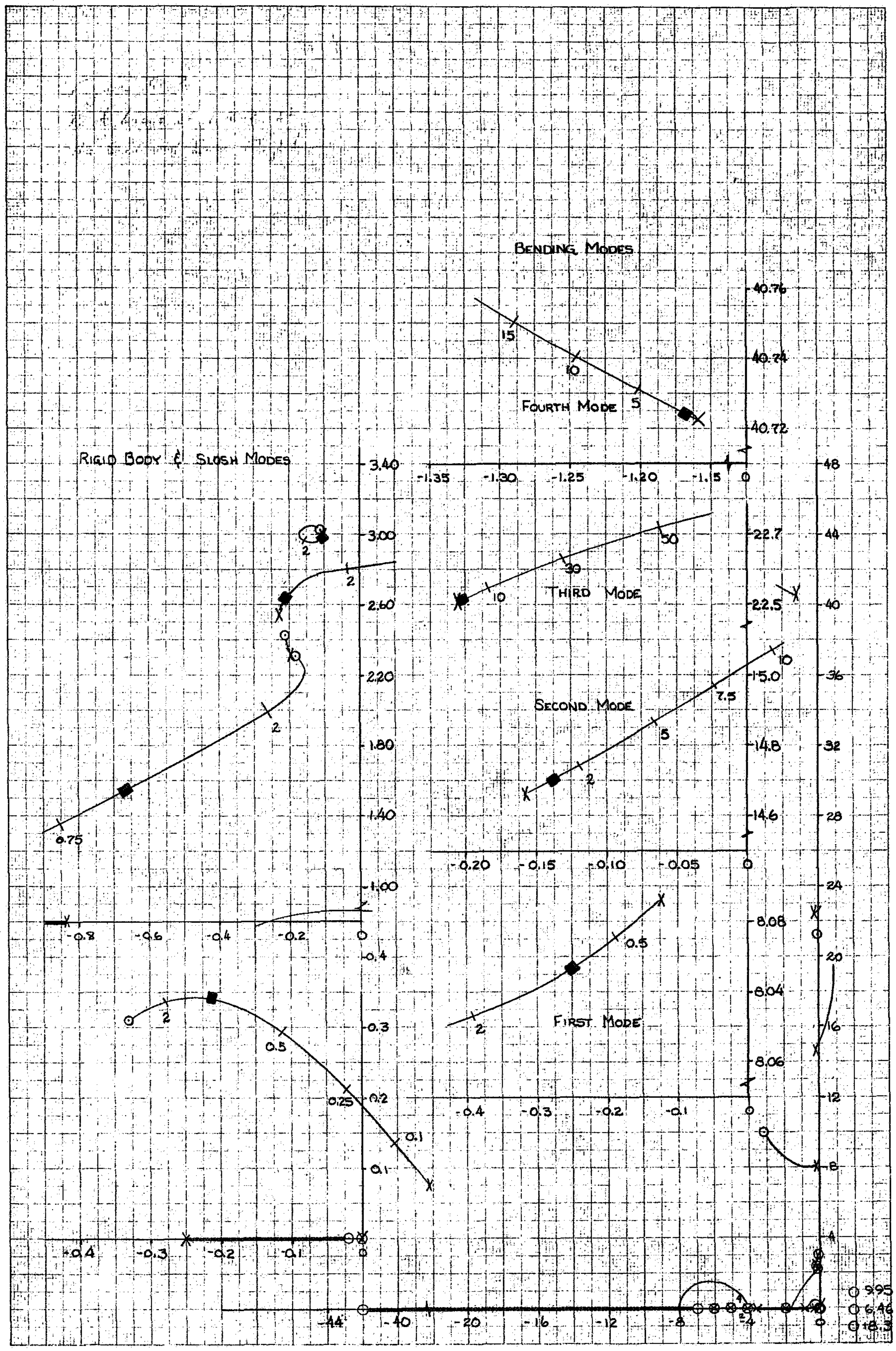


Figure C2. Root Locus Plot of LR-2 at 40 Seconds into Flight

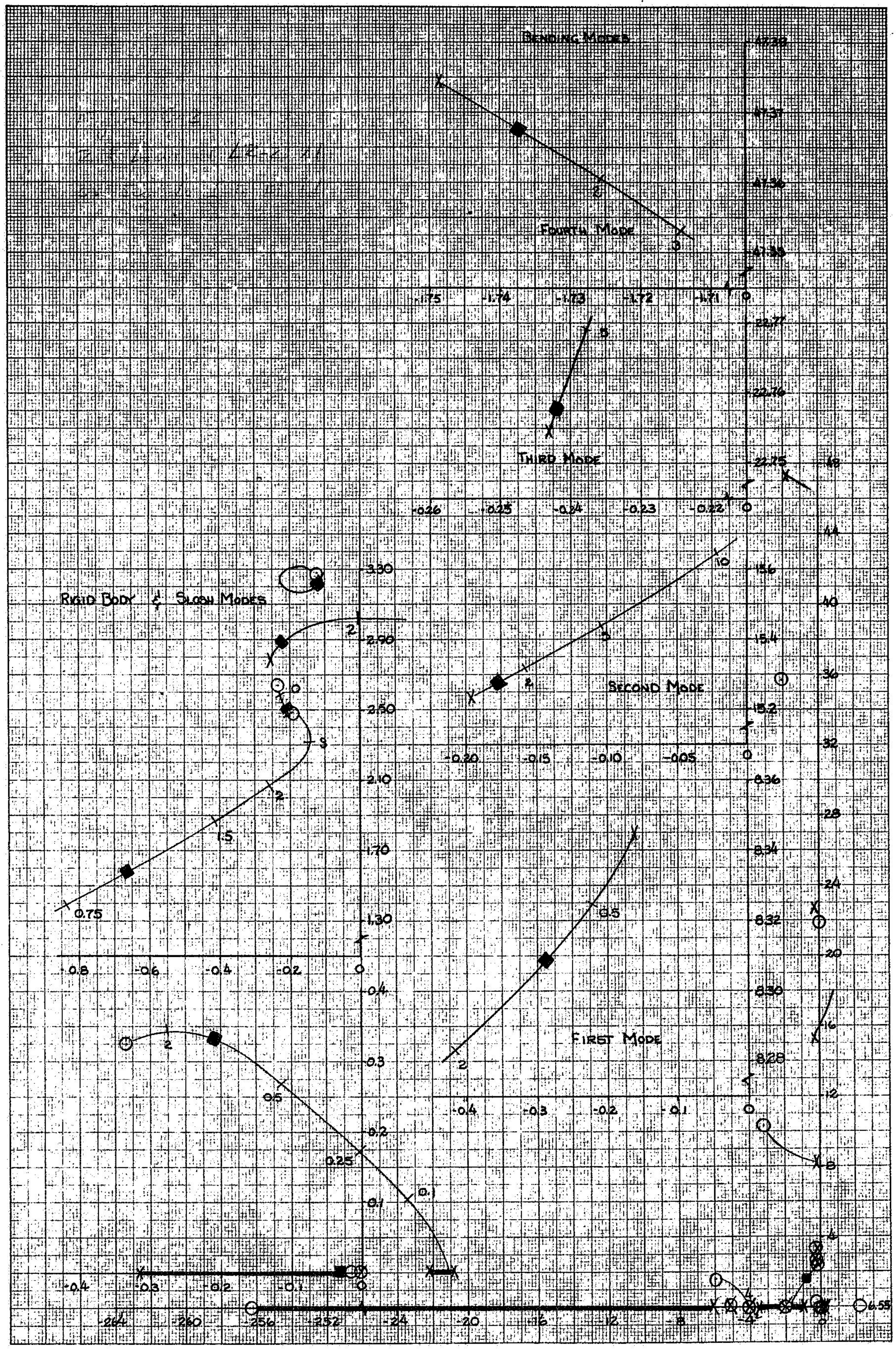


Figure C3. Root Locus Plot of LR-2 at 60 Seconds into Flight

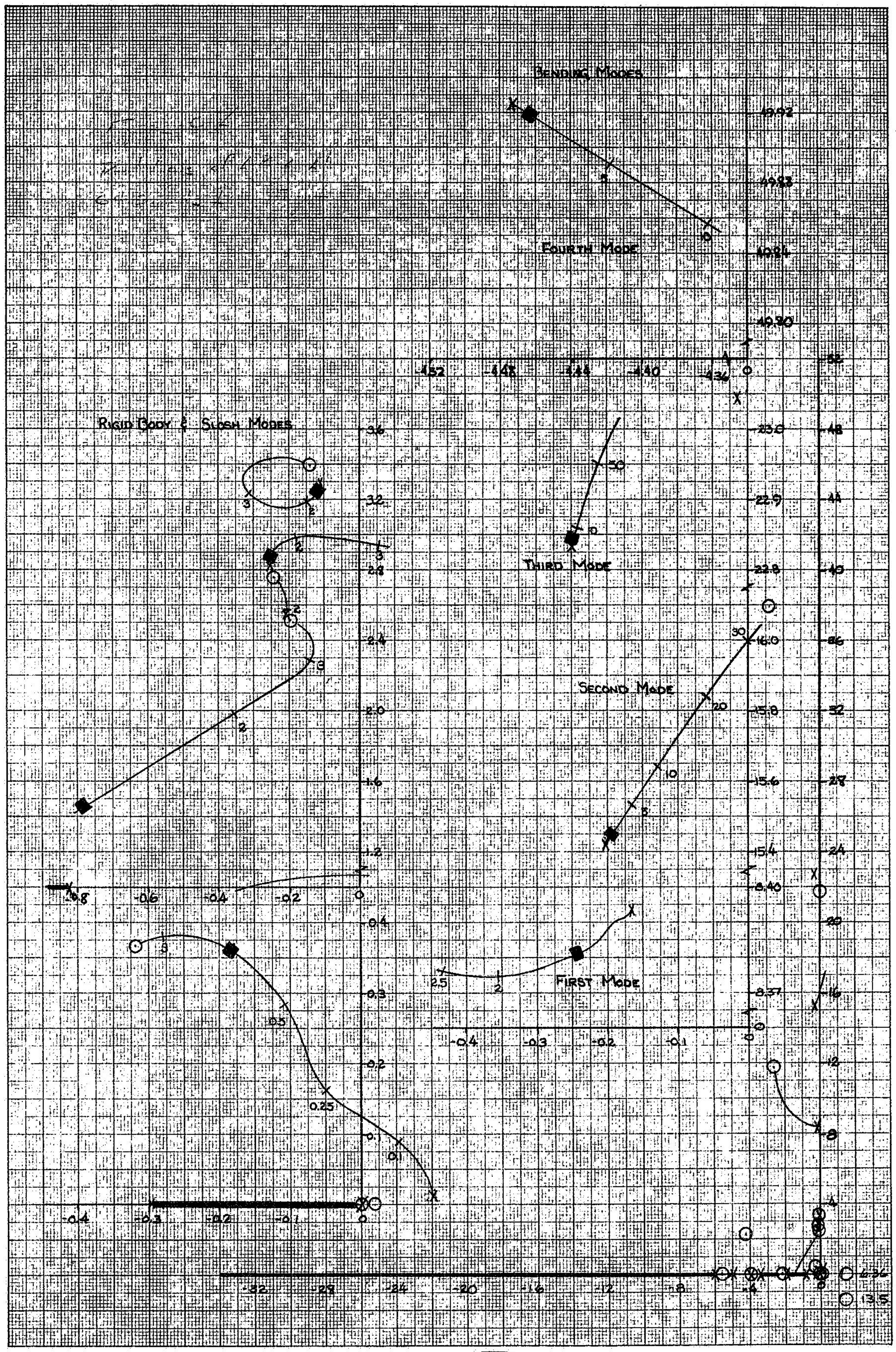


Figure C4. Root Locus Plot of LR-2 at 64 Seconds into Flight

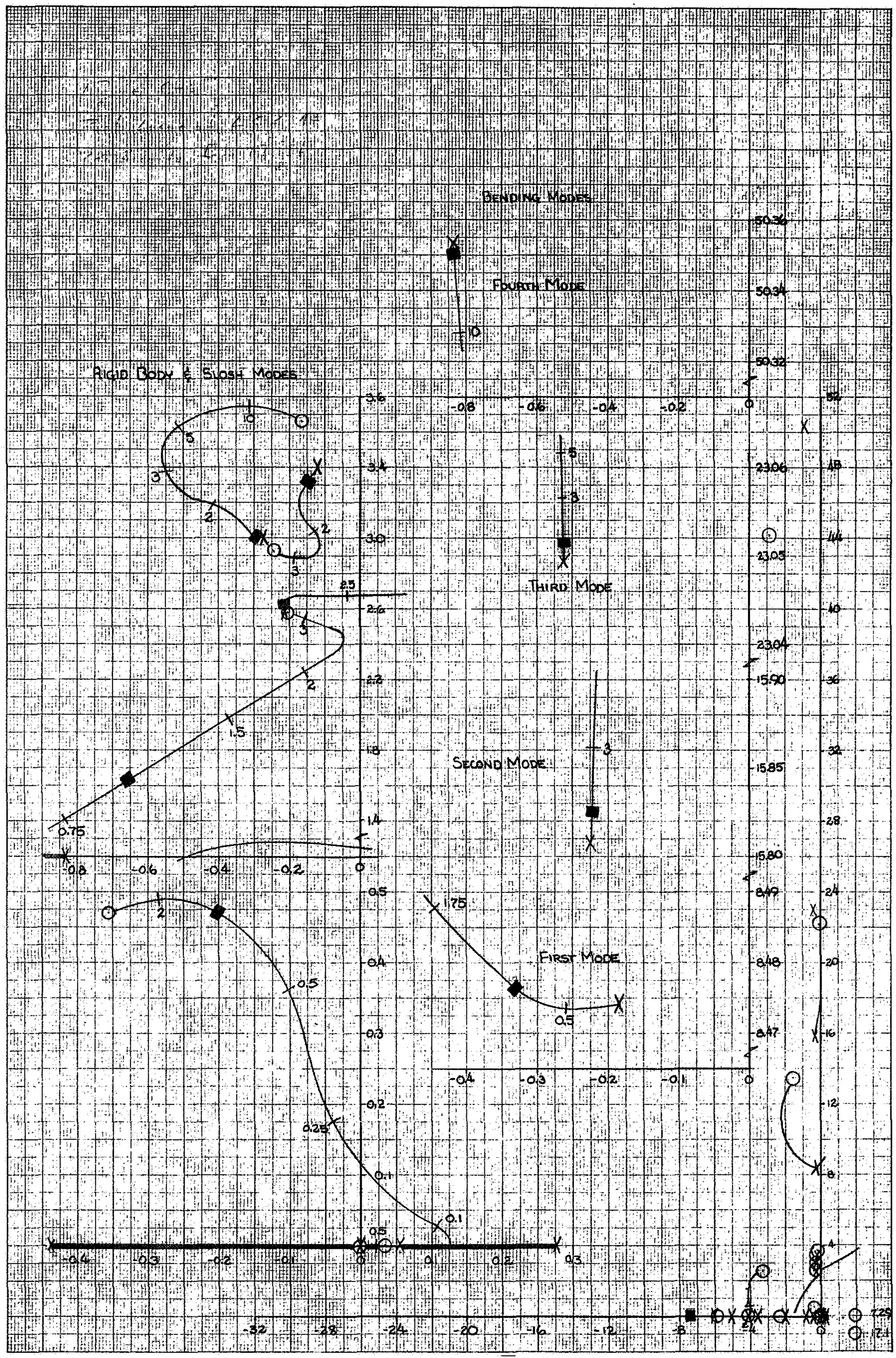


Figure C5. Root Locus Plot of LR-2 at 72 Seconds into Flight

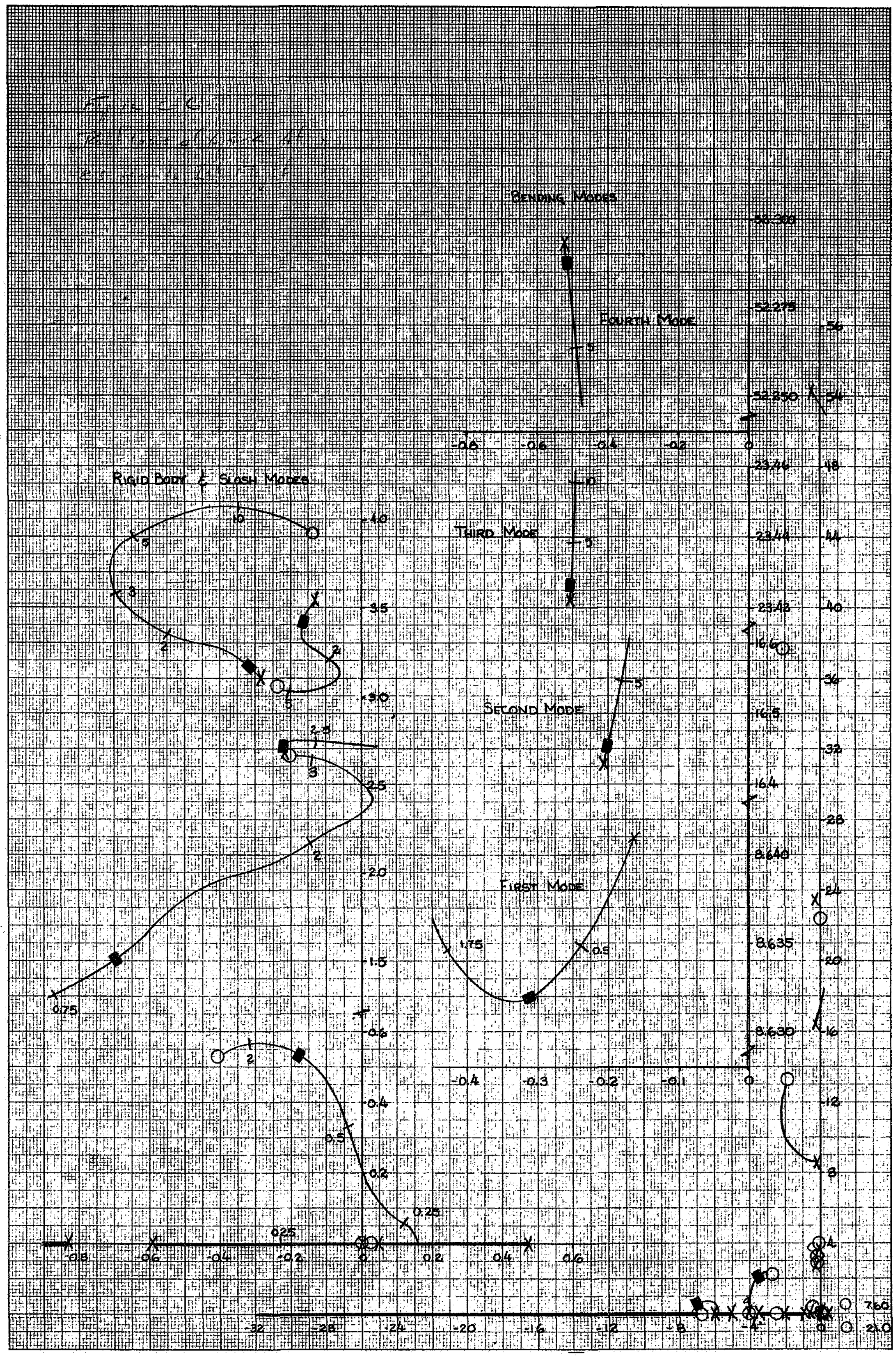


Figure C6. Root Locus Plot of LR-2 at 83 Seconds into Flight

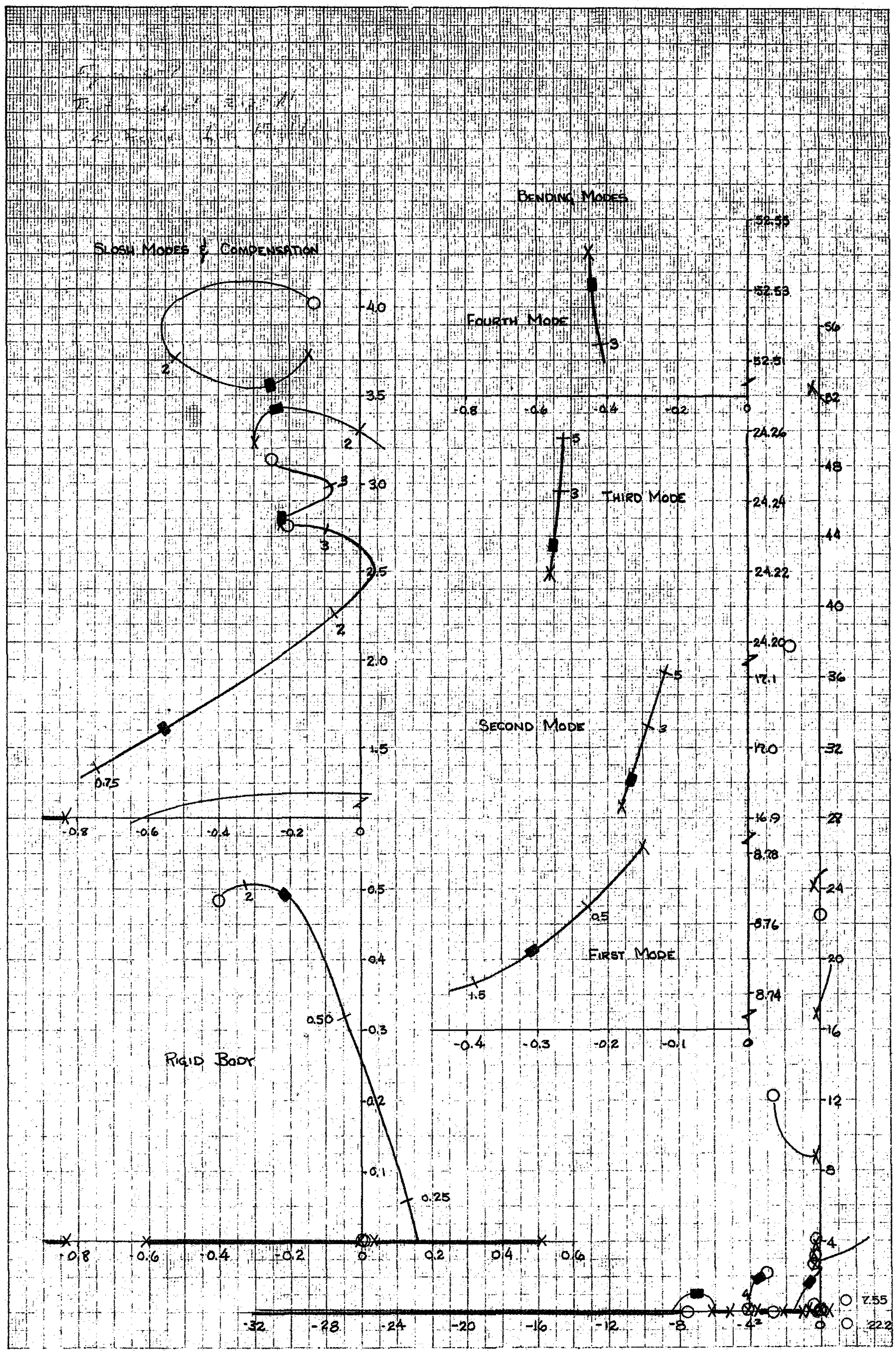


Figure C7. Root Locus **Plot of LR-2** at 92 Seconds into Flight

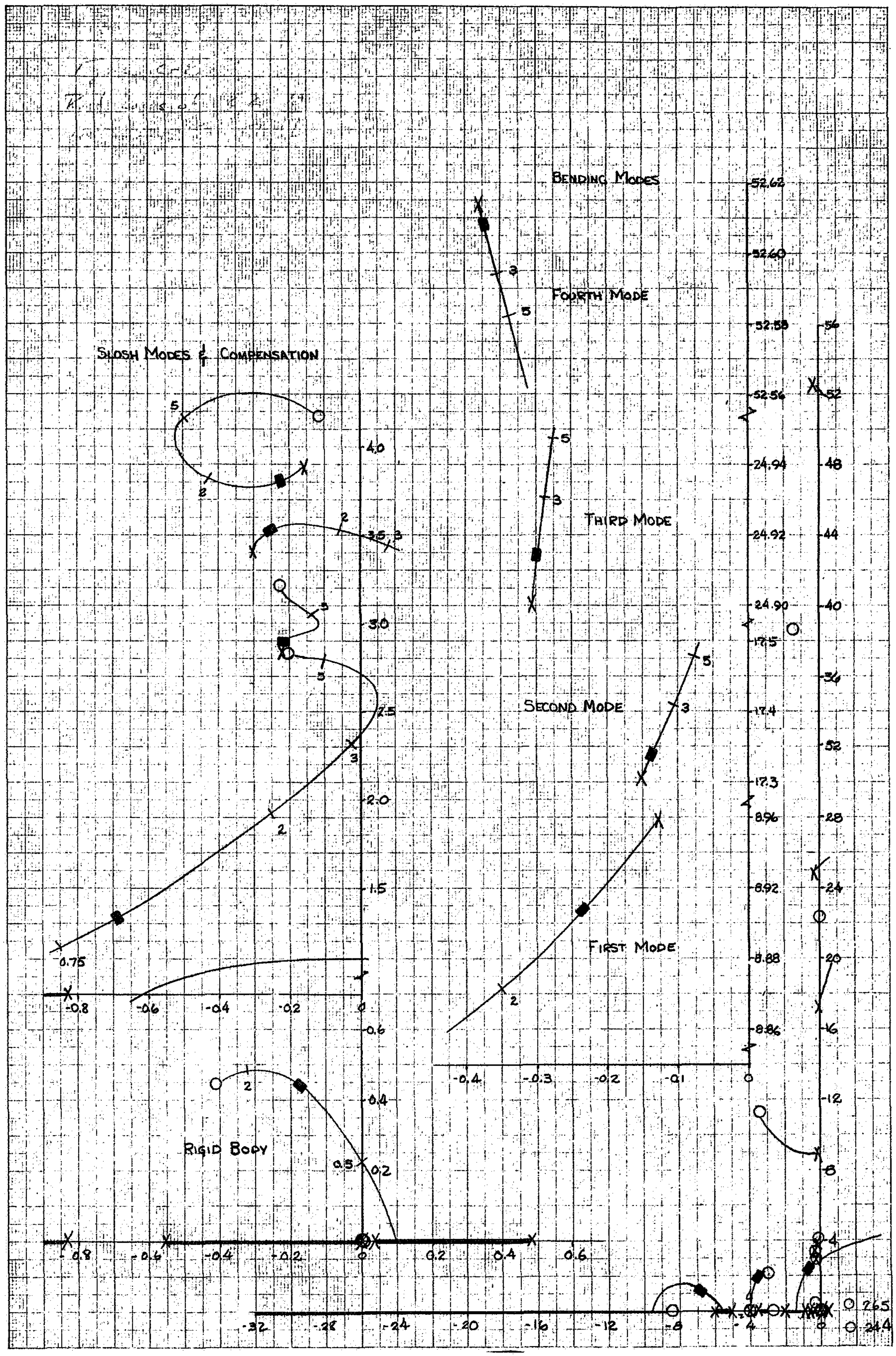


Figure C8. Root Locus Plot of LR-2 at 100 Seconds into Flight

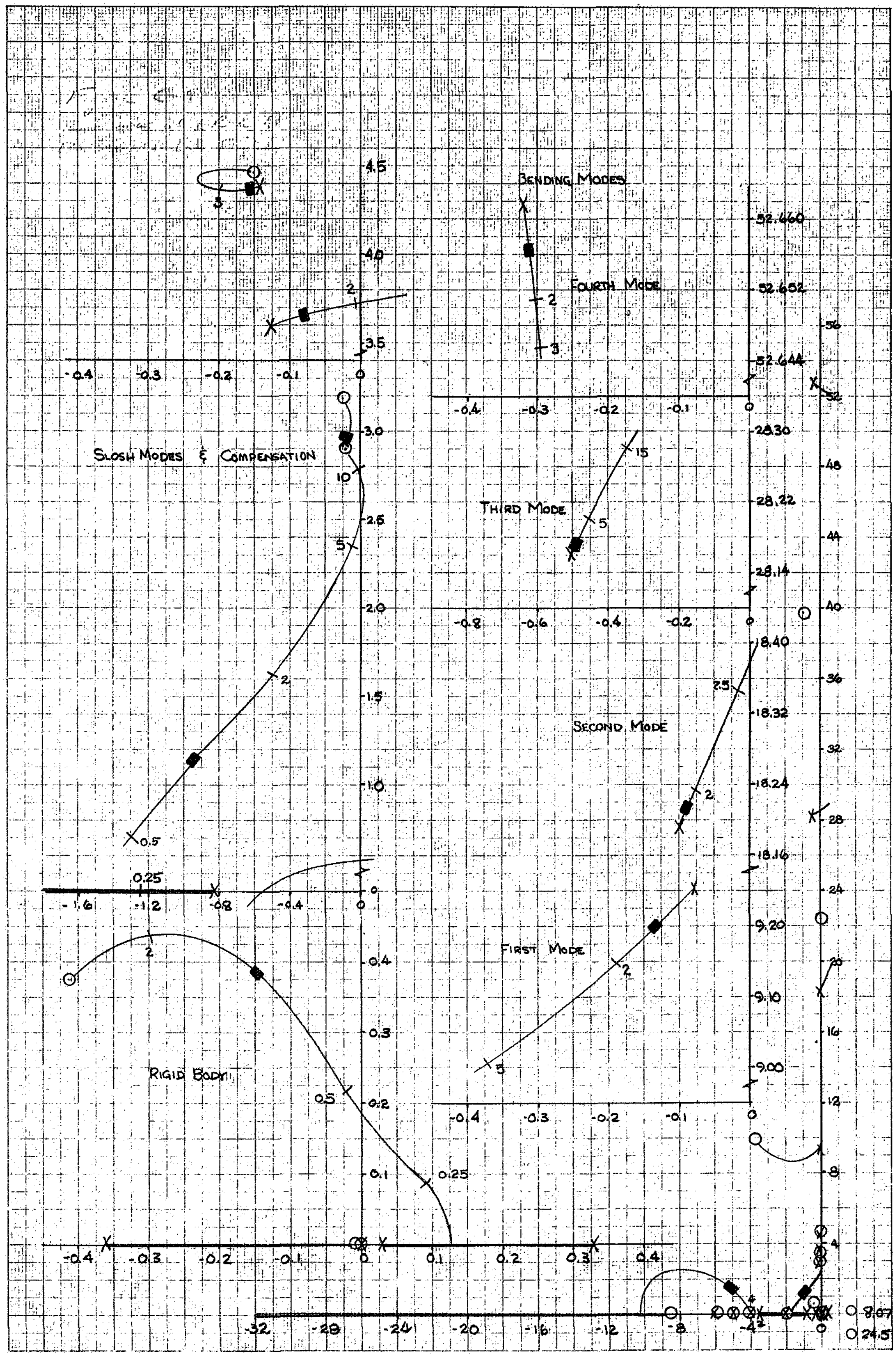


Figure C9. Root Locus Plot of LR-2 at 120 Seconds into Flight

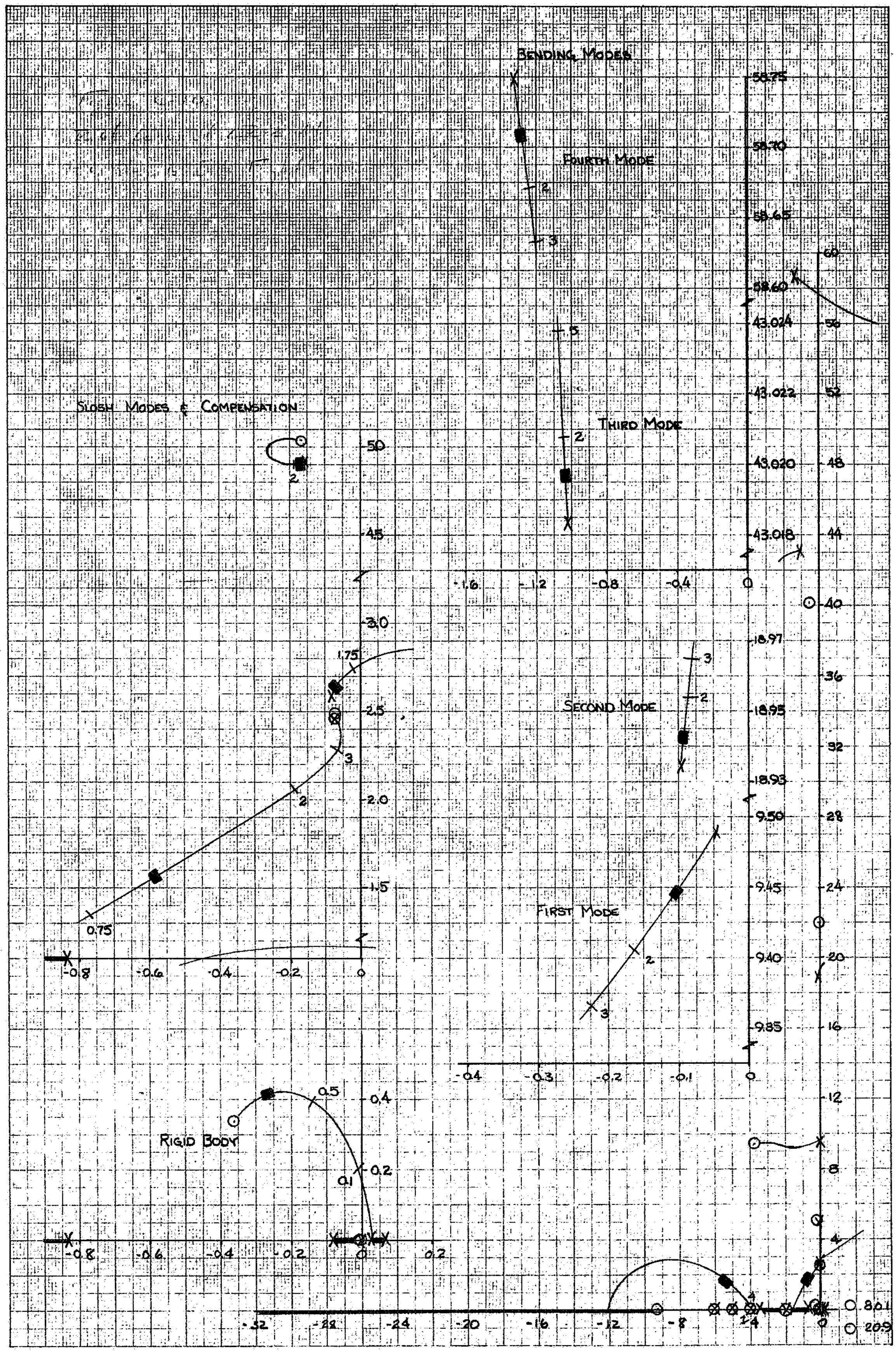


Figure C10. Root Locus Plot of LR-2 at 156 Seconds into Flight

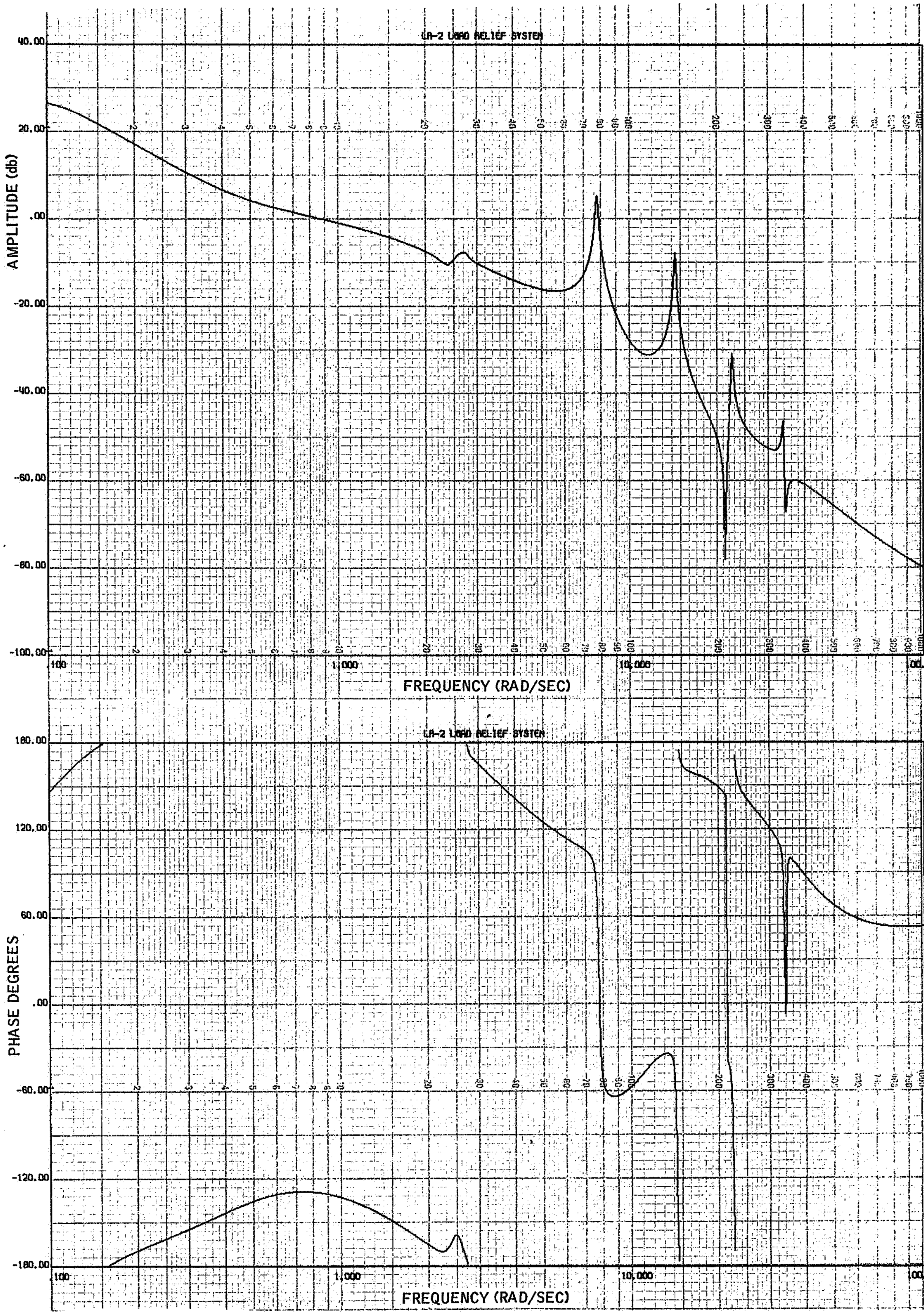


Figure C11. Frequency Response for Saturn V/Voyager with LR-2 Load Relief Control System at Eight Seconds into Flight

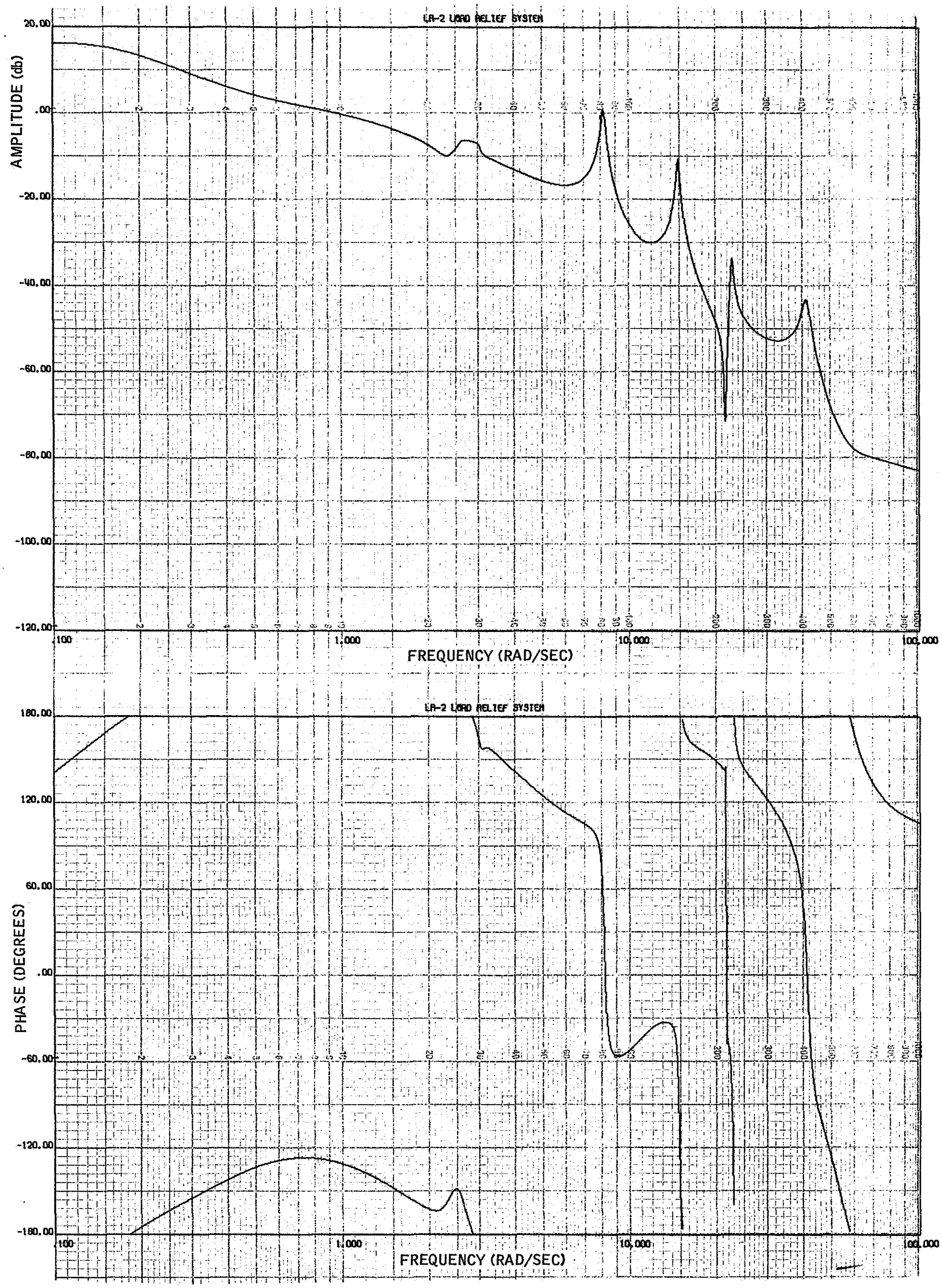


Figure C12. Frequency Response for Saturn V/Voyager with LR-2 Load Relief Control System at 40 Seconds into Flight

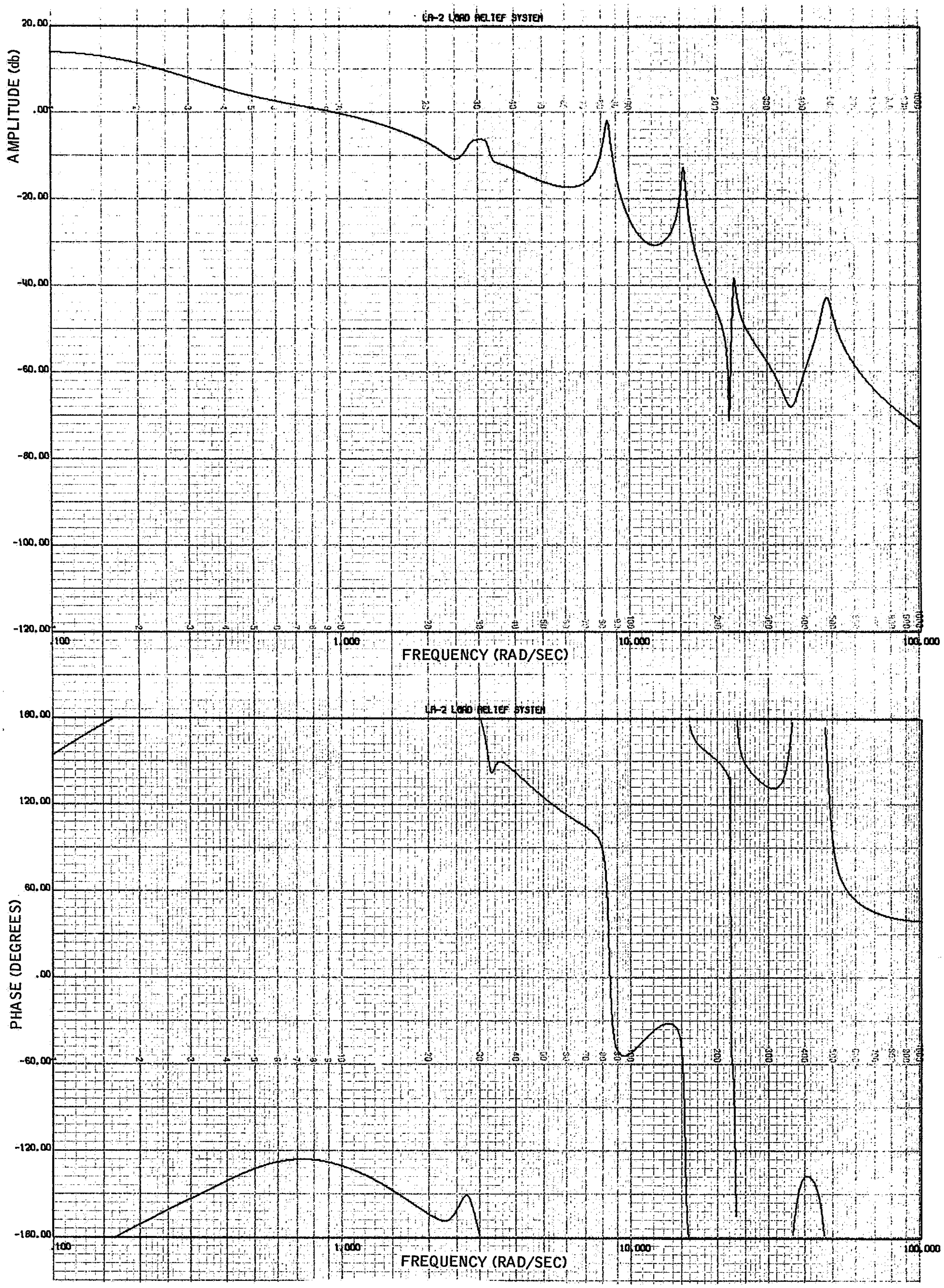


Figure C13. Frequency Response for Saturn V/Voyager with LR-2 Load Relief Control System at 60 Seconds into Flight

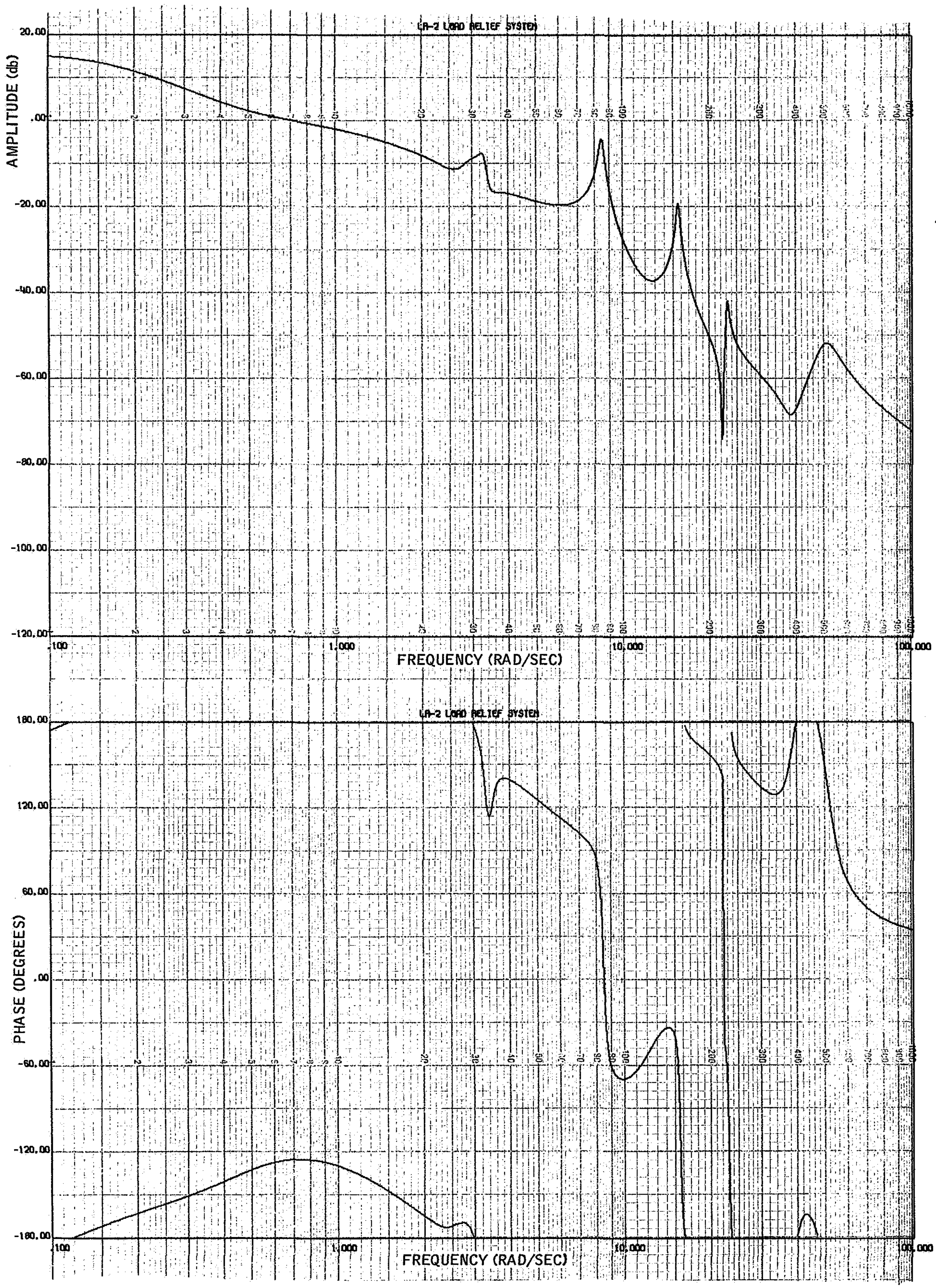


Figure C14. Frequency Response for Saturn V/Voyager with LR-2 Load Relief Control System at 64 Seconds into Flight

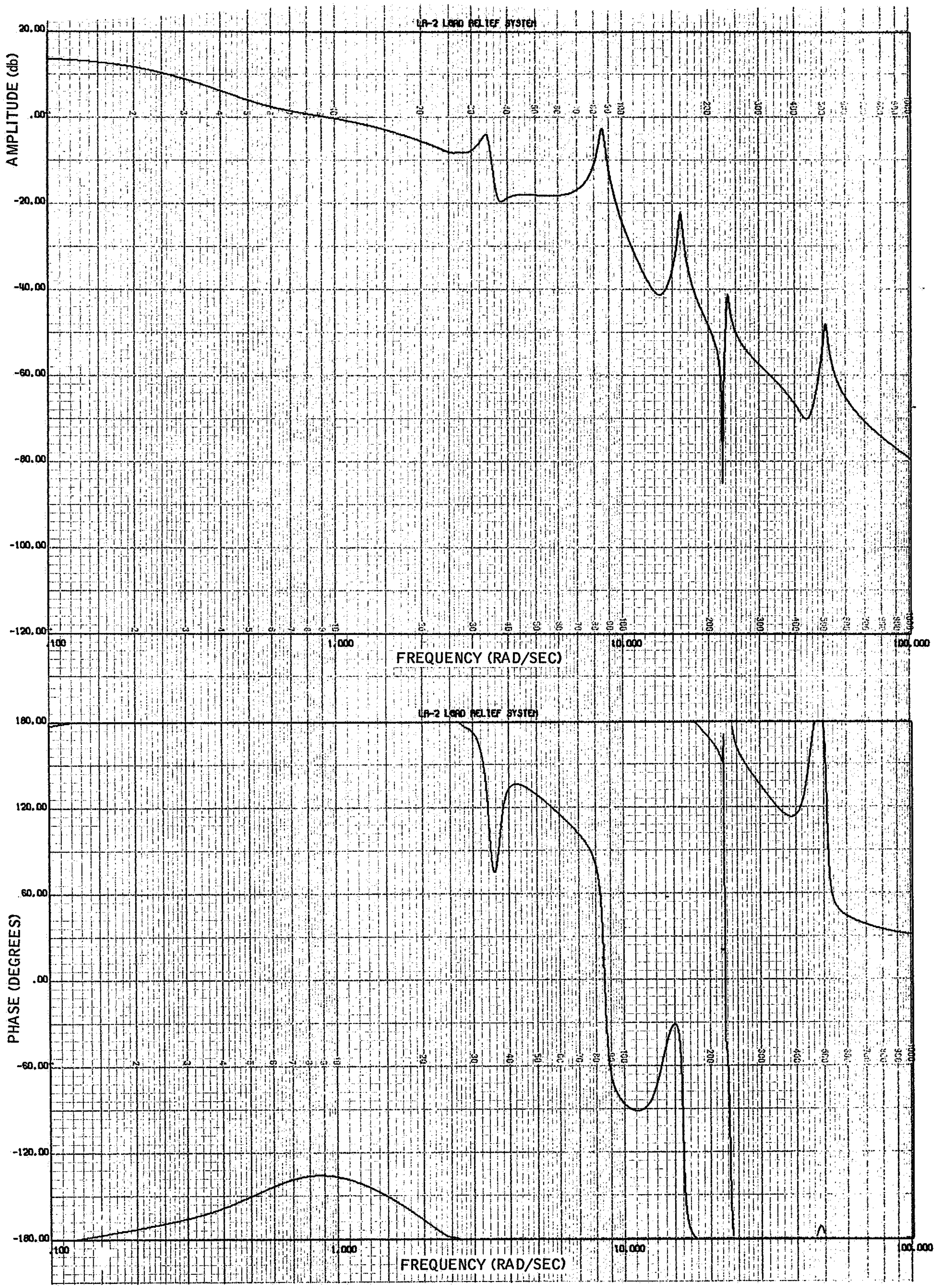
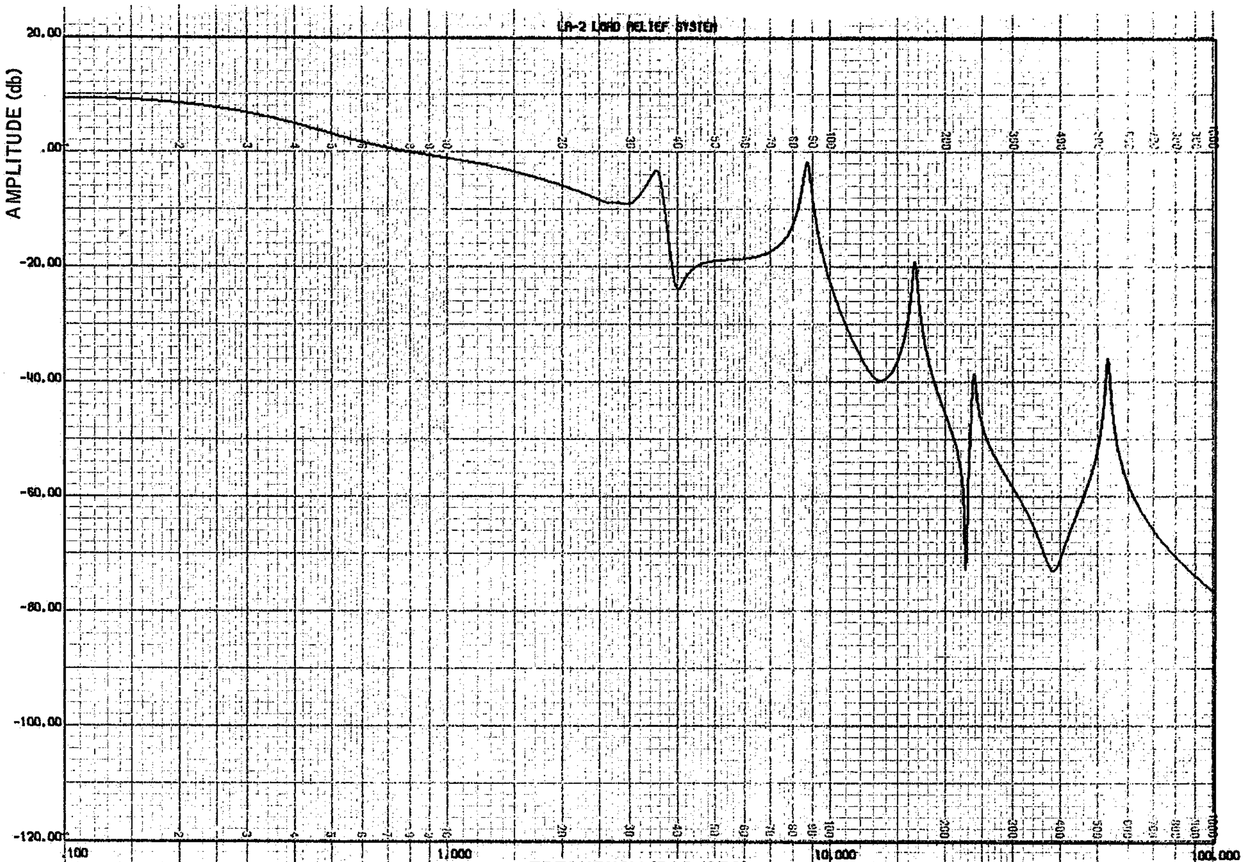


Figure C15. Frequency Response for Saturn V/Voyager with LR-2 Load Relief Control System at 72 Seconds into Flight



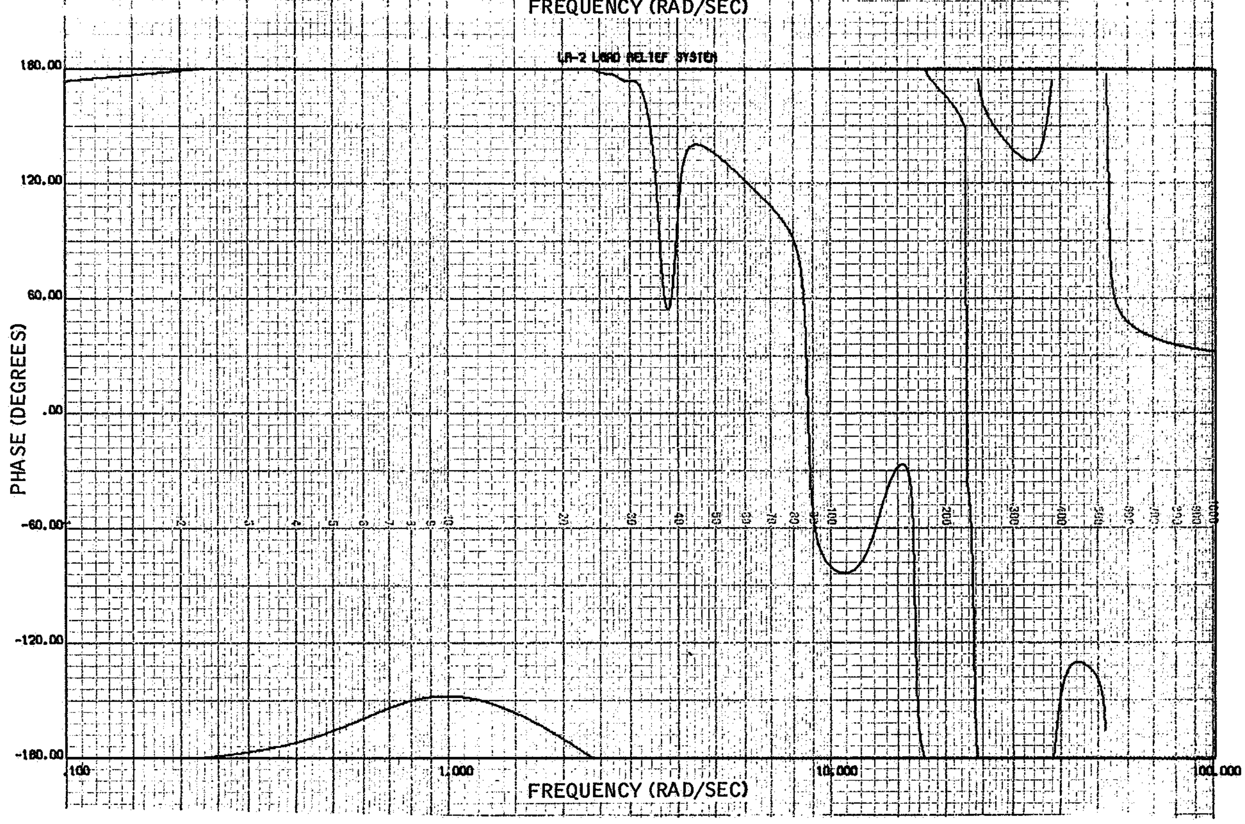


Figure C16. Frequency Response for Saturn V/Voyager with LR-2 Load Relief Control System at 83 Seconds into Flight

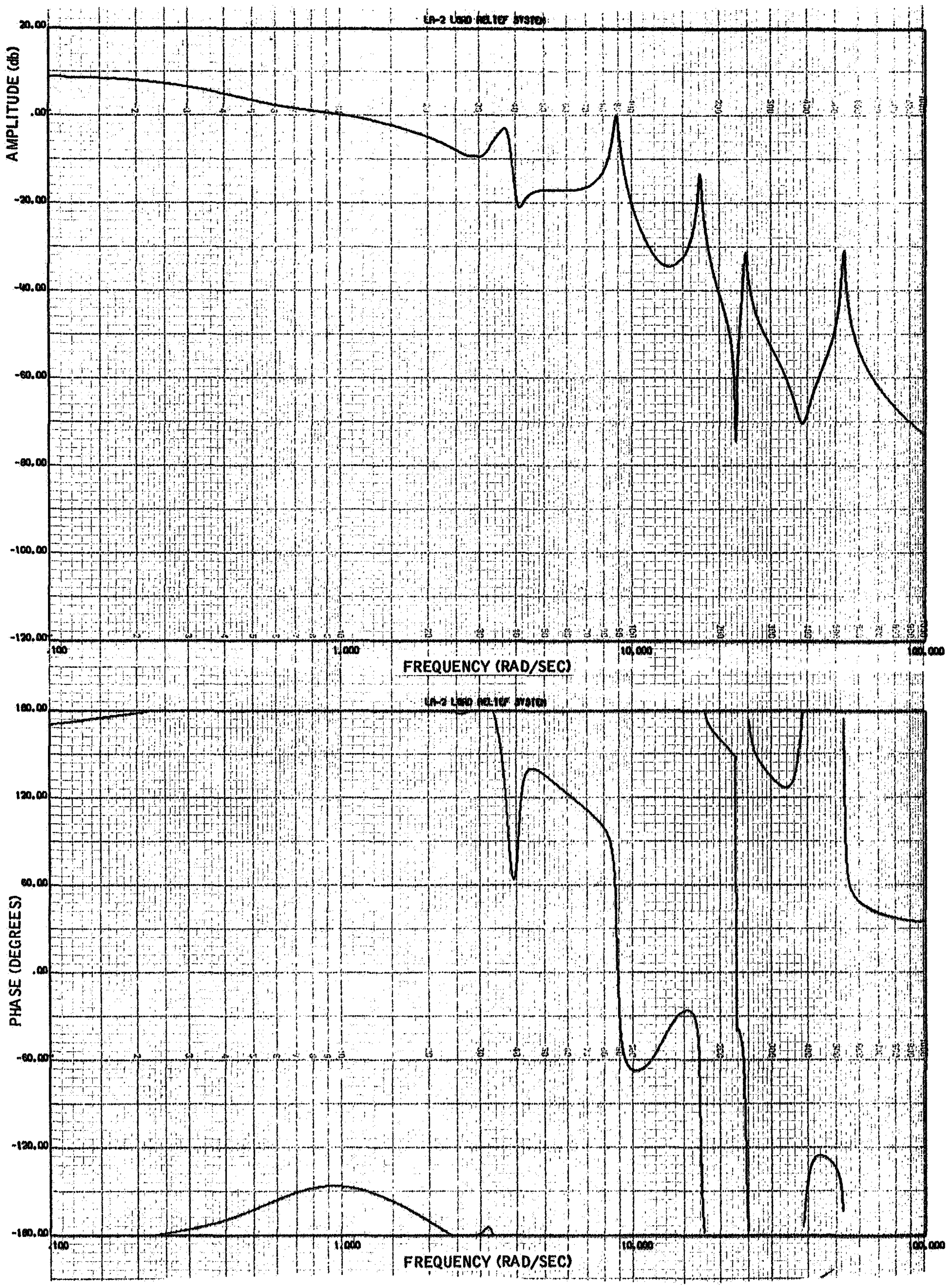


Figure C17. Frequency Response for Saturn V/Voyager with LR-2 Load Relief Control System at 92 Seconds into Flight

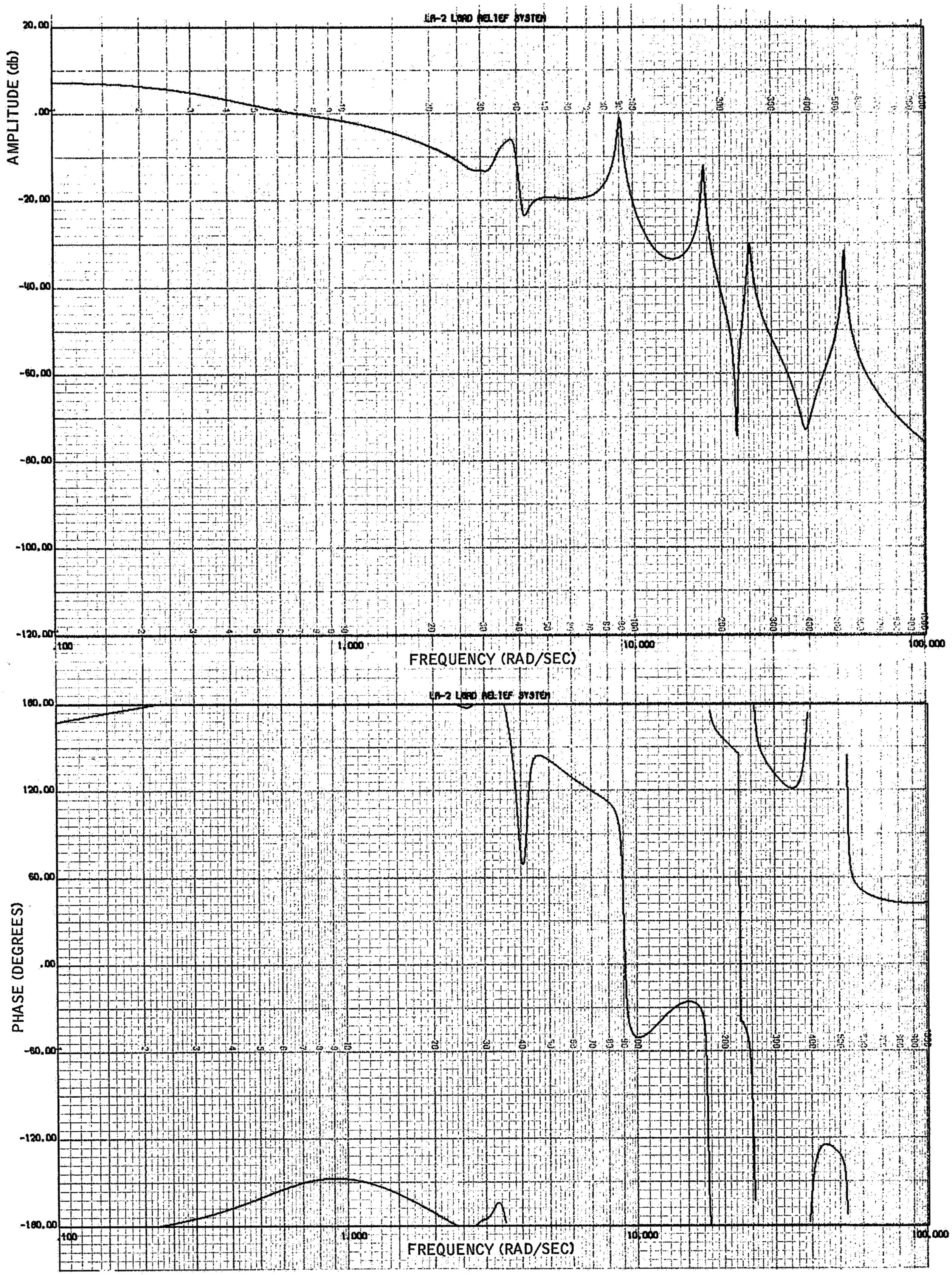


Figure C18. Frequency Response for Saturn V/Voyager with LR-2 Load Relief Control System at 100 Seconds into Flight

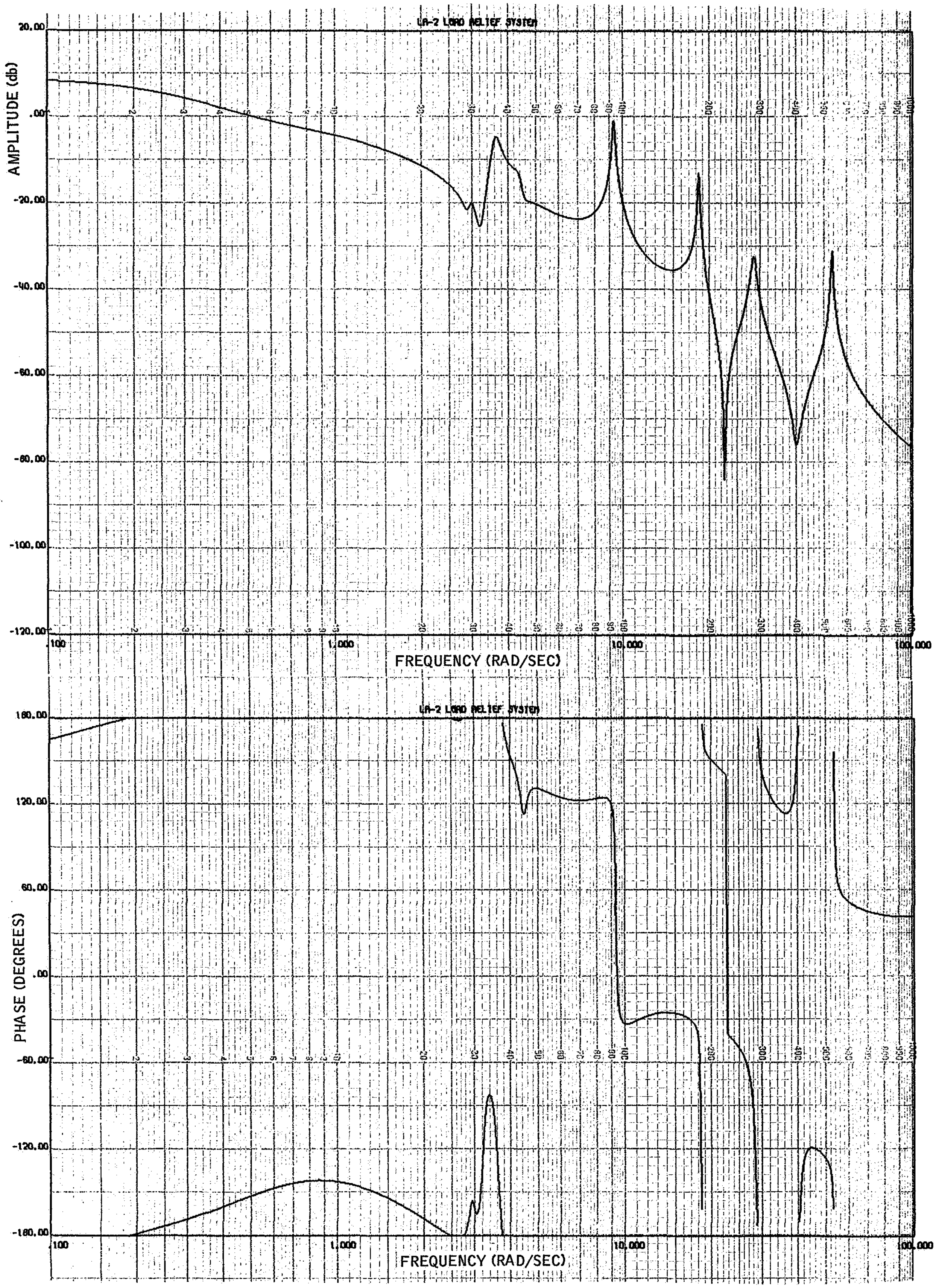


Figure C19. Frequency Response for Saturn V/Voyager with LR-2 Load Relief Control System at 120 Seconds into Flight

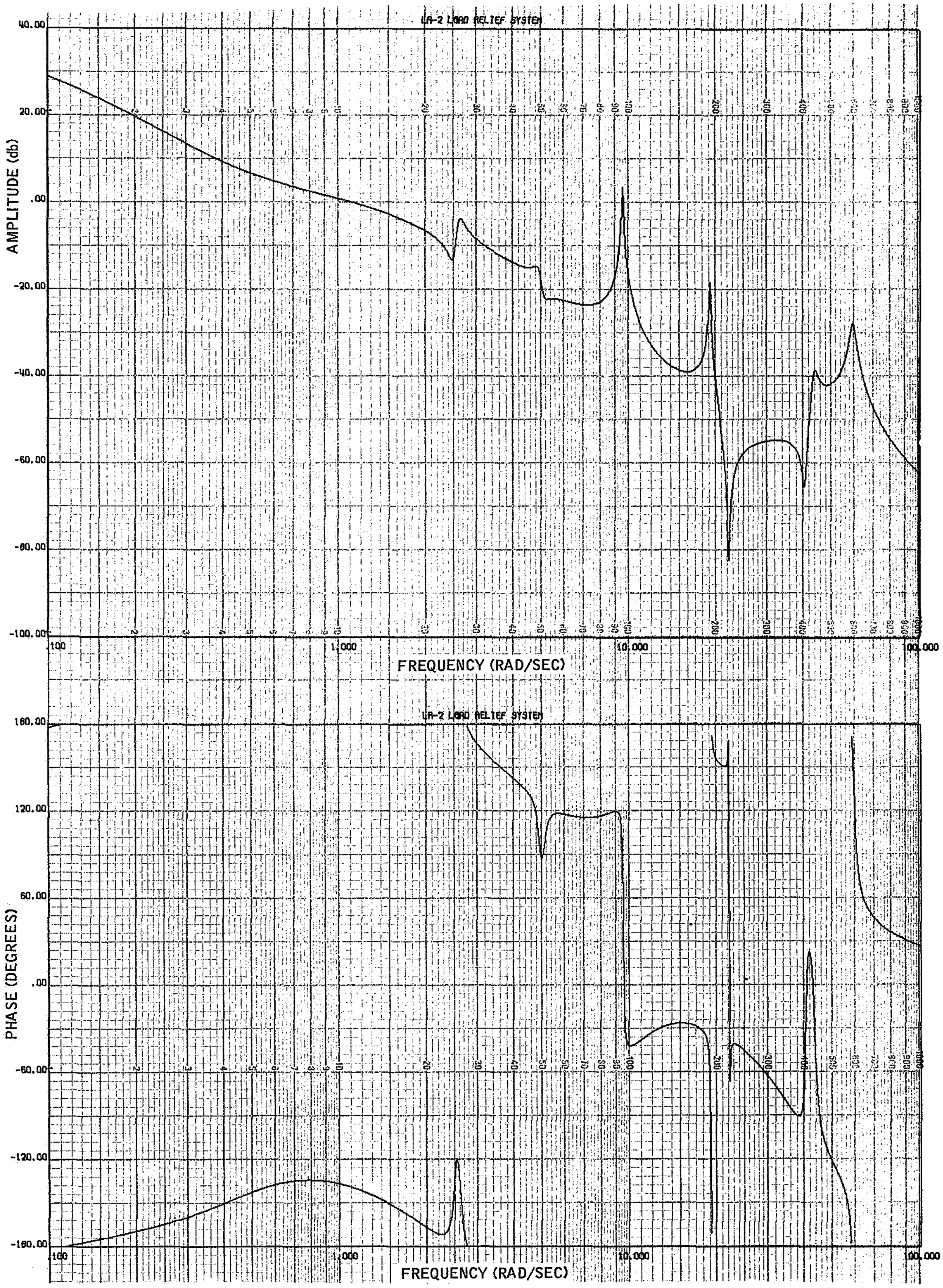


Figure C20. Frequency Response for Saturn V/Voyager with LR-2 Load Relief Control System at 156 Seconds into Flight

APPENDIX D

FLIGHT TRAJECTORY RESPONSES (ANALOG TIME-VARYING) FOR FINAL LR-2 CONTROL SYSTEM

This appendix contains the analog computer time-varying flight simulation trajectory responses. The data shown is for the final LR-2 control system.

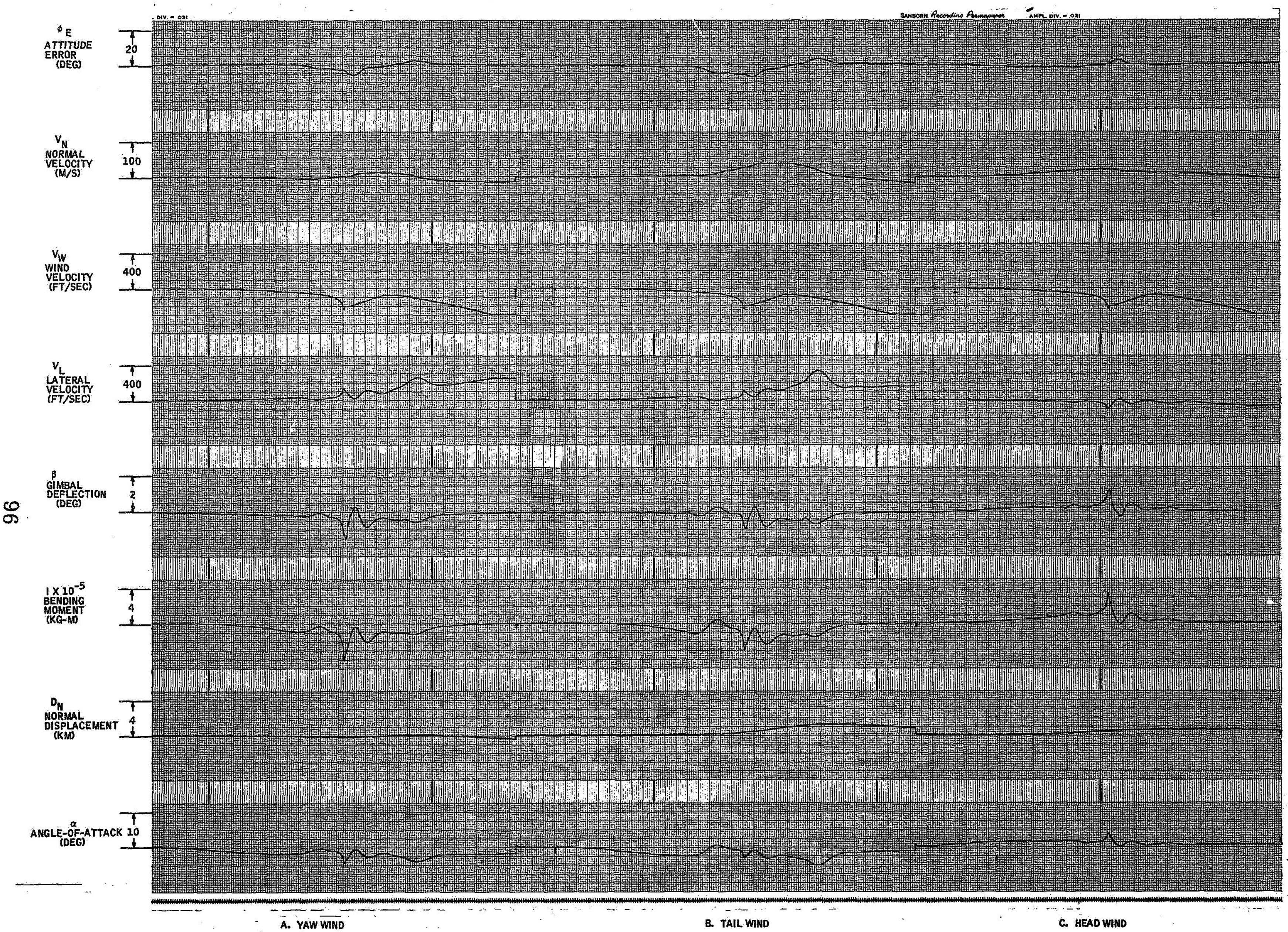


Figure D1. Trajectory Response for May-December Maximum q Wind

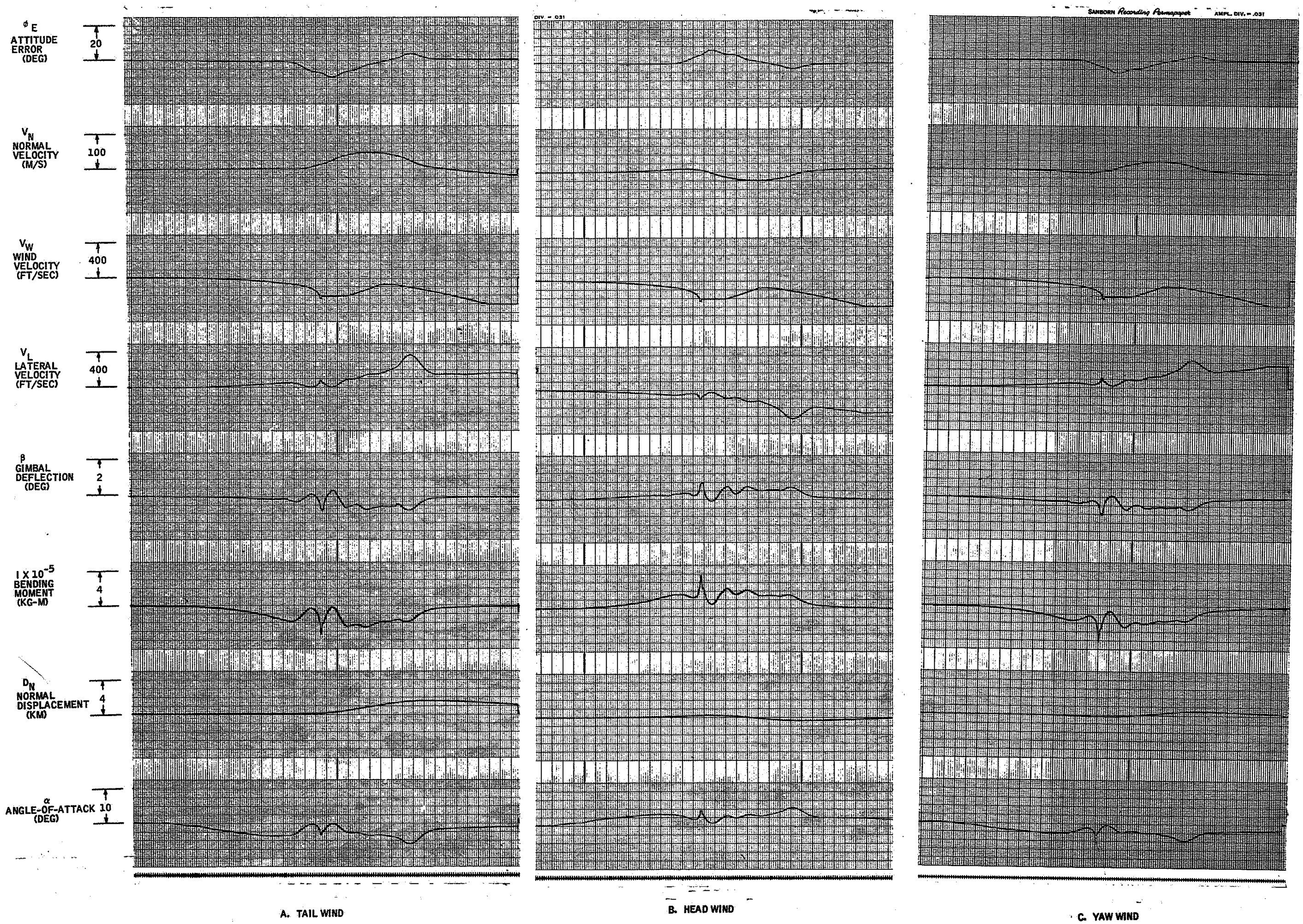


Figure D2. Trajectory Response for May-December Maximum $q\alpha$ Wind

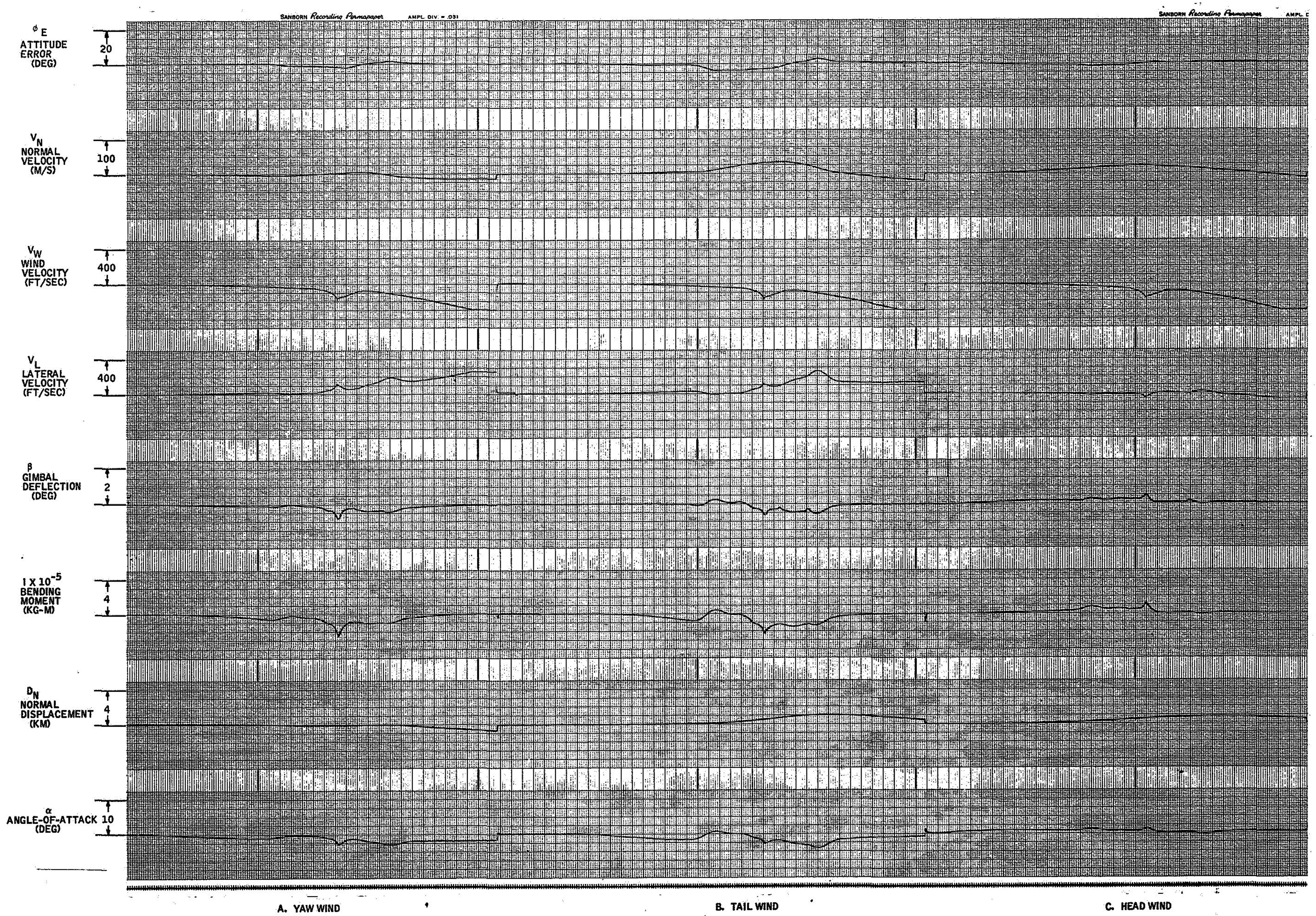


Figure D3. Trajectory Response for May-December Mach 2 Wind

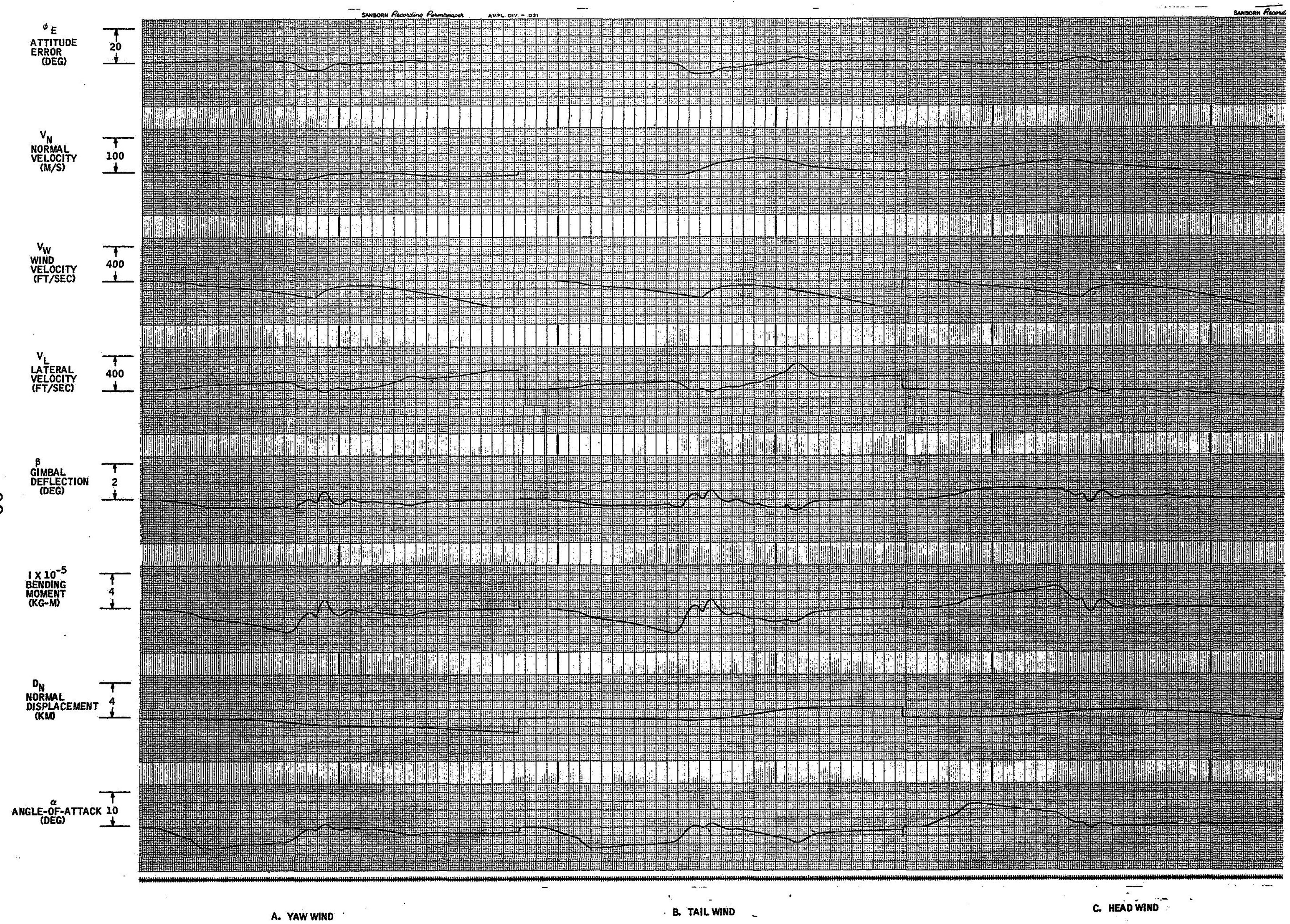


Figure D4. Trajectory Response for May-December MSFC Reverse Shear Wind

APPENDIX E
SYNTHESIS PROCEDURE

The synthesis procedure used to define feedback compensation in the LR-2 system is described in this appendix. Since development of this procedure was not an objective of the load relief study but only a by-product, only the basic ideas of the procedure are discussed. Nevertheless, the reader should be able to obtain a sufficient understanding of the procedure even though all the steps are not explained in detail.

Definition of the "preliminary LR-2" system was accomplished without any significant stability analysis. The LR-1 system was modified as required to meet trajectory performance requirements (active filters were replaced with passive filters and minor gain changes were made to provide acceptable stability). As a consequence, compensation used in the preliminary LR-2 system was not evaluated to determine if it was doing the job efficiently. Thus, an objective was established to develop a systematic procedure for defining the compensation. It was desirable to justify the compensation used in the preliminary LR-2 system or else to replace it with a more effective compensation.

To this end, the following observations were made:

- Trajectory performance is determined primarily by low-frequency characteristics of the system.
- Compensation is required only to satisfy stability constraints.
- Rate feedback is required only for stabilizing the rigid body, and its compensation is not a function of trajectory criteria but of stability criteria.

- Only a few frequency points on a frequency response plot of the vehicle-system open-loop transfer function are of real interest. These are the frequencies at which gain and phase margins are measured.

Thus, the required low-frequency attitude and acceleration feedback gains are defined by trajectory constraints (i. e., bending moment and terminal condition constraints). This task can be accomplished using a trajectory simulation by initially neglecting slosh and bending modes and by adding enough rate feedback to stabilize the rigid body.

Based on the above observations it was concluded that a frequency response requirement for feedback compensation could be established by examining only the critical frequency points at which gain and phase margins are measured. To recall, gain margin is measured at the point at which phase equals 180 degrees, and phase margin is measured at the point at which gain equals one. Since the booster was statically unstable, the frequency response plot of the stabilized vehicle open-loop transfer function will have the characteristic shown in Figure E1. Frequencies f_1 through f_4 are the discrete frequency points at which compensation requirements are to be established. That is, the objective was to specify a gain and phase requirement at each one of these frequency points and then, by curve-fitting, define a compensation on each feedback which would satisfy these requirements.

For example, consider the block diagram of a typical load relief control system which consists of attitude, attitude rate, and acceleration feedbacks (see Figure E2). The transfer functions of the vehicle, ϕ/β, $\dot{\phi}/\beta$, and $\ddot{Z}/\beta$, attitude gain, K_ϕ, and acceleration gain, K_z, are known. The problem is to define the compensations $G_1(s)$, $K_{\dot{\phi}} G_2(s)$, and $G_3(s)$. The gain and phase constraints specified for the study were:

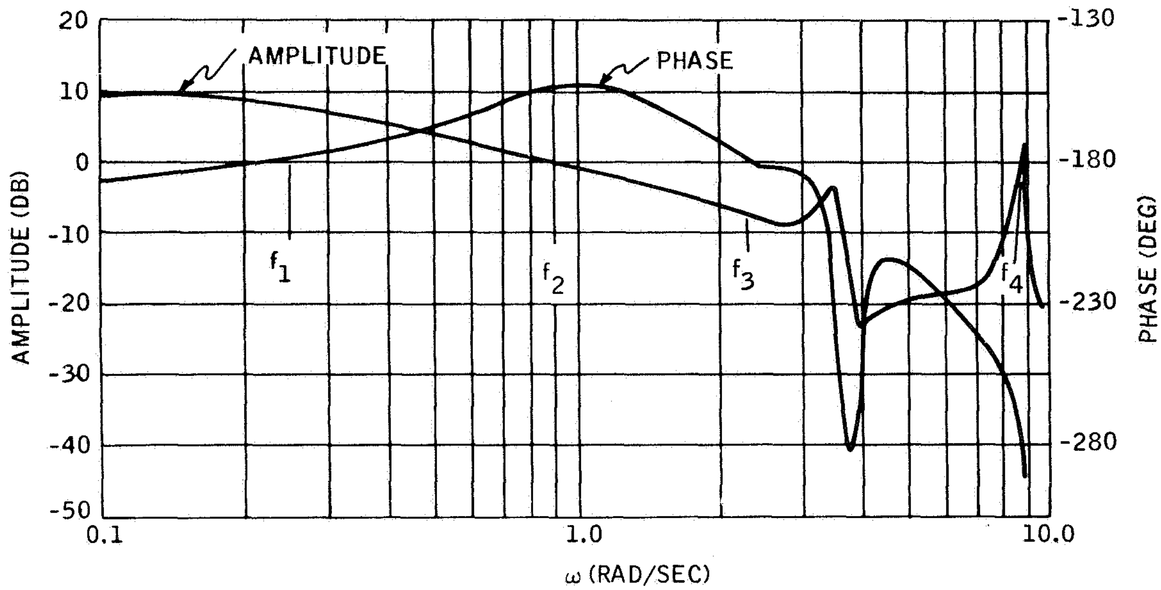


Figure E1. Typical Vehicle - System Open-Loop Transfer Function

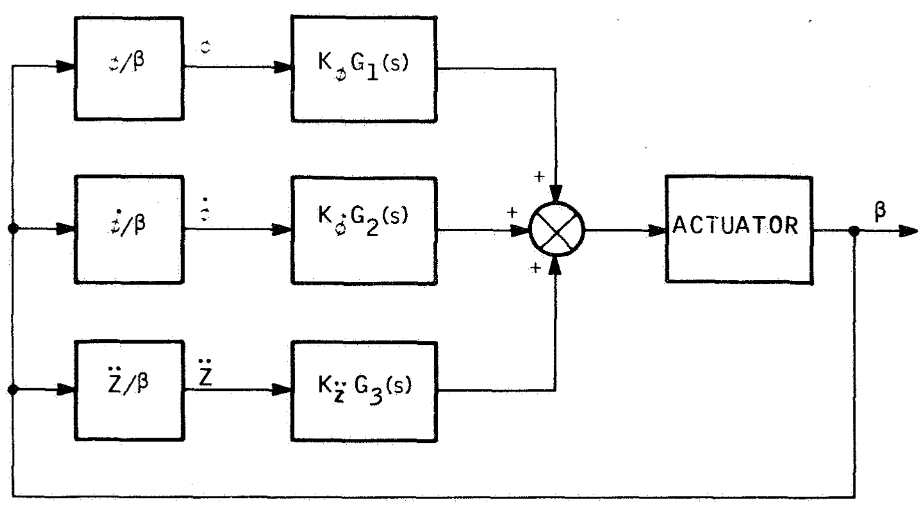


Figure E2. General Load Relief - Vehicle Closed-Loop Block Diagram

- Six-decibel gain margin at all frequencies
- Thirty-degree phase margin at rigid-body frequency
- Forty-degree phase margin at slosh and bending modes.

Examination of Figure E1 shows the first constraint must be imposed at frequencies f_1 and f_3. The second constraint is imposed at f_2 and the third at f_4. If we define the vectors which correspond to each feedback as:

$$\left(\frac{\phi}{\beta}\right) K_{\phi} G_1 = \vec{R} = a_{\phi} + b_{\phi_j}$$

$$\left(\frac{\dot{\phi}}{\beta}\right) K_{\dot{\phi}} G_2 = \vec{R} = a_{\dot{\phi}} + b_{\dot{\phi}_j}$$

$$\left(\frac{\ddot{Z}}{\beta}\right) K_{\ddot{z}} G_3 = \vec{R}_z = a_{\ddot{z}} + b_{\ddot{z}_j}$$

and the resultant of these vectors to be

$$\vec{R} = (a_{\phi} + a_{\dot{\phi}} + a_{\ddot{z}}) + (b_{\phi} + b_{\dot{\phi}} + b_{\ddot{z}})_j$$

we can impose the following stability constraints:

- At f_1:

1) $|\vec{R}| = [a_{\dot{\phi}} + (a_{\phi} + a_{\ddot{z}}]^2 + [b_{\dot{\phi}} + (b_{\phi} + b_{\ddot{z}})]^2 \geq 4.0$

and

2) $b_{\phi} + b_{\dot{\phi}} + b_{\ddot{z}} \leq 0,\ a_{\phi} + a_{\dot{\phi}} + a_{\ddot{z}} \leq 0$

- At f_2:

3) $|\vec{R}| = [a_{\dot{\phi}} + (a_{\phi} + a_{\ddot{z}})]^2 + [b_{\dot{\phi}} + (b_{\phi} + b_{\ddot{z}})]^2 > 1.0$

and

$$4) \quad \text{Tan } 30° = 0.577 \leq \frac{b_{\phi} + b_{\dot{\phi}} + b_{\ddot{z}}}{a_{\phi} + a_{\dot{\phi}} + a_{\ddot{z}}}$$

- At f_3:

$$5) \quad |\vec{R}| = [a_{\dot{\phi}} + (a_{\phi} + a_{\ddot{z}})] + [b_{\dot{\phi}} + (b_{\phi} + b_{\ddot{z}})]^2 \leq 0.25$$

and

$$6) \quad b_{\phi} + b_{\dot{\phi}} + b_{\ddot{z}} \cong 0, \; a_{\phi} + a_{\dot{\phi}} + a_{\ddot{z}} < 0$$

In the study it was not necessary to consider the phase constraint at f_4 since consideration of the above constraints automatically satisfied this additional constraint. This may not be the case in other applications, however, and should be considered.

The constraints defined above can be plotted on a vector diagram as shown in Figure E3.

The approach taken at this point was to map these constraints onto a vector diagram with $a_{\dot{\phi}}$ along the abscissa and $b_{\dot{\phi}}$ along the ordinate, as shown in Figure 4. Attitude and acceleration feedbacks are then treated as independent variable and the rate becomes the dependent variable. This is so because the attitude and acceleration feedback compensation determines where the constraints lie on this rate vector diagram. By comparing the free-vehicle rate vector, $\dot{\phi}/\beta$, and the location of the constraint boundaries, it is possible to determine the desired compensation on the attitude and acceleration feedbacks. The goal in this procedure is to minimize the rate gain required at f_2 and maximize the allowable rate vector magnitude at f_3. To assure the constraints are satisfied at all flight conditions of interest

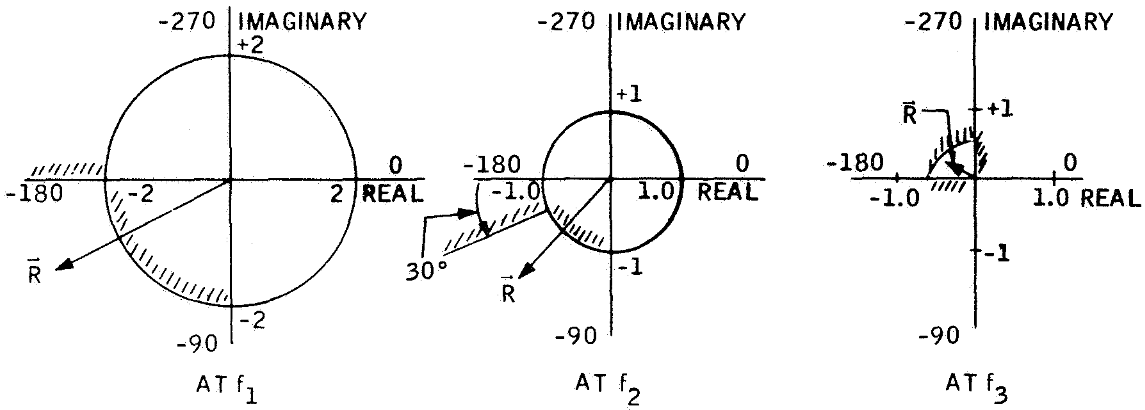


Figure E3. Vector Diagram Showing Stability Constraints

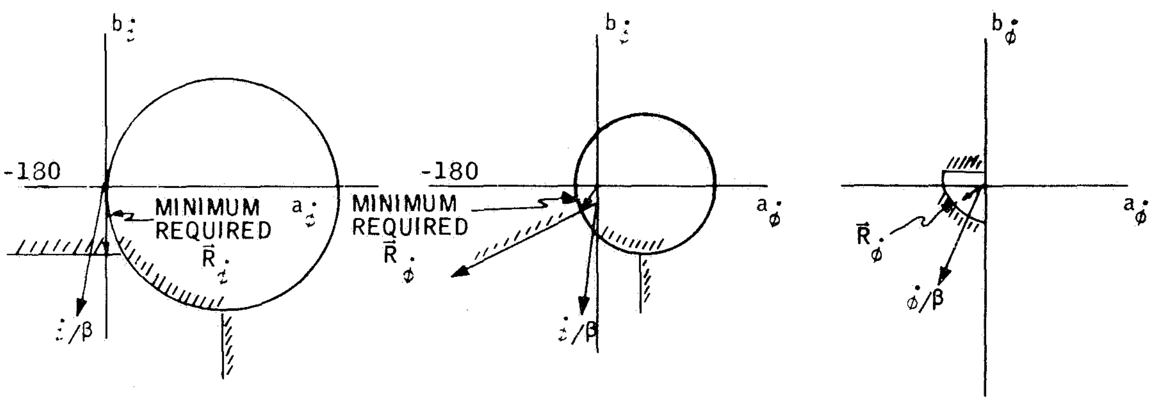


Figure E4. Mapping of Stability Constraints onto a Rate Vector Diagram the constraints for all these conditions are plotted on the same vector diagrams to establish the strongest boundaries. Satisfying these constraints at these frequencies on a frequency response plot. Combinations of filters can be fitted to these constraints to result in a filter definition. This is done for each of the feedbacks. Once the filters are defined, the open-loop vehicle-system frequency response can be computed to verify the analysis.

This procedure provided a means of defining compensation directly in terms of the stated stability constraints. There are, of course, some problems with the approach which must still be resolved. One problem, for example, is how to determine the critical frequency points. A first guess can be made by examining the free-vehicle transfer functions. However, since the compensation chosen will affect these points somewhat, the analysis may require examining additional frequency points.

It is expected that this technique can be further refined and perhaps programmed on a digital computer. Ultimately, it is hoped this procedure will be combined with a procedure for establishing system parameters to satisfy trajectory constraints. Most likely this will involve the use of a simplified time-varying flight simulation. The primary advantage of this synthesis procedure is that system parameters are defined directly in terms of performance requirements.